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HIGH-BRIGHTNESS DIODE LASERS FOR BLUE-GREEN APPLICATIONS

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Experimental investigations of the physics of self-pumped photorefractive phase-conjugators are performed. Particular emphasis is placed on studying the properties of backward stimulated photorefractive scattering (BSPS) conjugators in $BaTiO_3$, and on attempts to demonstrate self-pumped phase-conjugation in GaAs. The phase-conjugate reflectivity of BSPS conjugations in $BaTiO_3$ is shown to be significantly enhanced by the use of feedback. An experimental comparison of three distinctly different geometries for feedback-enhanced backward stimulated photorefractive scattering (FE-BSPS) is made. In one case, the feedback is found to stabilize the reflectivity, while in the other case, it greatly enhances the peak reflectivity.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

The goal of this program is to investigate the physics of special classes of self-pumped phase-conjugators that are potentially useful for the scaling of 0.85 μm diode lasers to high powers. On this program, two classes of self-pumped conjugators have been examined. The main emphasis of the program has been on backward stimulated scattering conjugators using ferroelectric oxides, such as $BaTiO_3$. Field-enhanced two-wave mixing conjugators in semiconductors, such as GaAs, are also being investigated.

An important advantage of self-pumped phase-conjugators that operate via backward stimulated photorefractive scattering (BSPS) and feedback-enhanced backward stimulated photorefractive scattering (FE-BSPS) is that no total internal reflections are involved. The damage thresholds of the BSPS conjugators are consequently less dependent on surface damage mechanisms than the total internal reflection phase-conjugate mirrors (TIR-PCMs). Also, since many (but not all) $BaTiO_3$ crystals exhibit their fastest response rates for the backward (small period) gratings, phase-conjugation via BSPS should have a faster response time than self-pumped conjugators involving forward (large period) gratings. Finally, the BSPS and FE-BSPS geometries are well-suited to mosaic array implementation, another important advantage for scaling to the large beam diameters inevitably associated with high power operation.

This interim report will describe details of several of our major accomplishments on this program to-date. Section 2 deals with our results on the BSPS and FE-BSPS conjugators using $BaTiO_3$. We begin Section 2.1 by describing the close analogy between stimulated photorefractive scattering and other types of stimulated scattering. We then present our observations of a previously rare phenomena — phase-conjugation via BSPS. Feedback enhancement geometries borrowed from the stimulated Brillouin scattering literature are applied to the improvement of BSPS conjugator performance in Section 2.2. Stability and fidelity issues relevant to our goals for the remainder of the program are discussed in Sections 2.3 and 2.4, respectively. Section 2.5 is a discussion of some possible inter-filament and/or inter-crystal cross-talk mechanisms that should help maintain very good fidelity for large beam areas. A summary of our accomplishments to-date, our plans for the remainder of the program, and an outline of remaining issues relevant to the coupling of several crystals in large-area mosaic-matrices are briefly reviewed in Section 2.6. The second part of this report, Section 3, discusses self-pumped conjugation using field enhanced two-wave mixing in GaAs. The basic features of these potential devices are outlined in Section 3.1, followed in Section 3.2 by a description of progress on preliminary experiments using these materials. Three abstracts and summaries and one paper submitted to Physical Review Letters (all supported either in part or in full by this program) are included as Appendices.

SECTION 2

BACKWARD STIMULATED PHOTOREFRACTIVE SCATTERING (BSPS) CONJUGATORS

2.1 STIMULATED PHOTOREFRACTIVE SCATTERING (SPS)

The use of the "stimulated scattering" terminology to describe stimulated photorefractive scattering (SPS), stimulated Rayleigh scattering (SRLS), stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS) dates back to the original discovery of stimulated Raman scattering by Eckhardt et al. in 1962.[1] Beam collimation, spectral narrowing, and the existence of a threshold were cited as evidence that the process was closely analogous to stimulated emission. In a subsequent theoretical paper, Hellwarth[2] gave a quantum mechanical description of the effect. Shen and Bloembergen[3] later showed that the effect can also be described classically; they nevertheless continued to call these processes stimulated in analogy to Einstein's stimulated emission of radiation. Since then, it has been widely used to describe processes in which a single pump laser beam of frequency ω and wavevector k_0 is coherently scattered to $(\omega+\delta, k_0+\Delta k_0)$ by some kind of an excitation in a nonlinear optical medium. The same term has been applied to a wide range of closely analogous processes mediated variously by polaritons (stimulated polariton scattering), entropy waves (stimulated Rayleigh scattering), molecular orientational excitations (stimulated Rayleigh-wing scattering), and so forth (for a review, see, for example, Shen).[4] In SPS, the mediating excitation is a photorefractive grating that can persist for minutes or days in the dark and that has time constants ranging from minutes to tens of picoseconds or less depending on the wavelength, and the temperature, and roughly inversely on intensity. Thus, the effect was quite naturally called stimulated photorefractive scattering when it was simultaneously predicted[5] and discovered[6] in $BaTiO_3$ in 1985.

Interestingly, the phase-conjugate properties of backward stimulated scattering processes were not recognized until 1972 by Zel'dovich et al.[7] Since then, the phase-conjugate nature of the backscattering has been successfully exploited in a wide range of applications, most notably to the correction of aberrations induced by thermally loaded laser amplifiers.[8]

2.1.1 Forward and Backward SPS

Both forward and backward stimulated photorefractive scattering (FSPS and BSPS, respectively, again by analogy to the well-known forward and backward stimulated Raman scattering effects) occur in $BaTiO_3$. The mechanism for FSPS, which is commonly referred to as "beam fanning," is illustrated in Figure 1. The laser beam enters the crystal and refracts

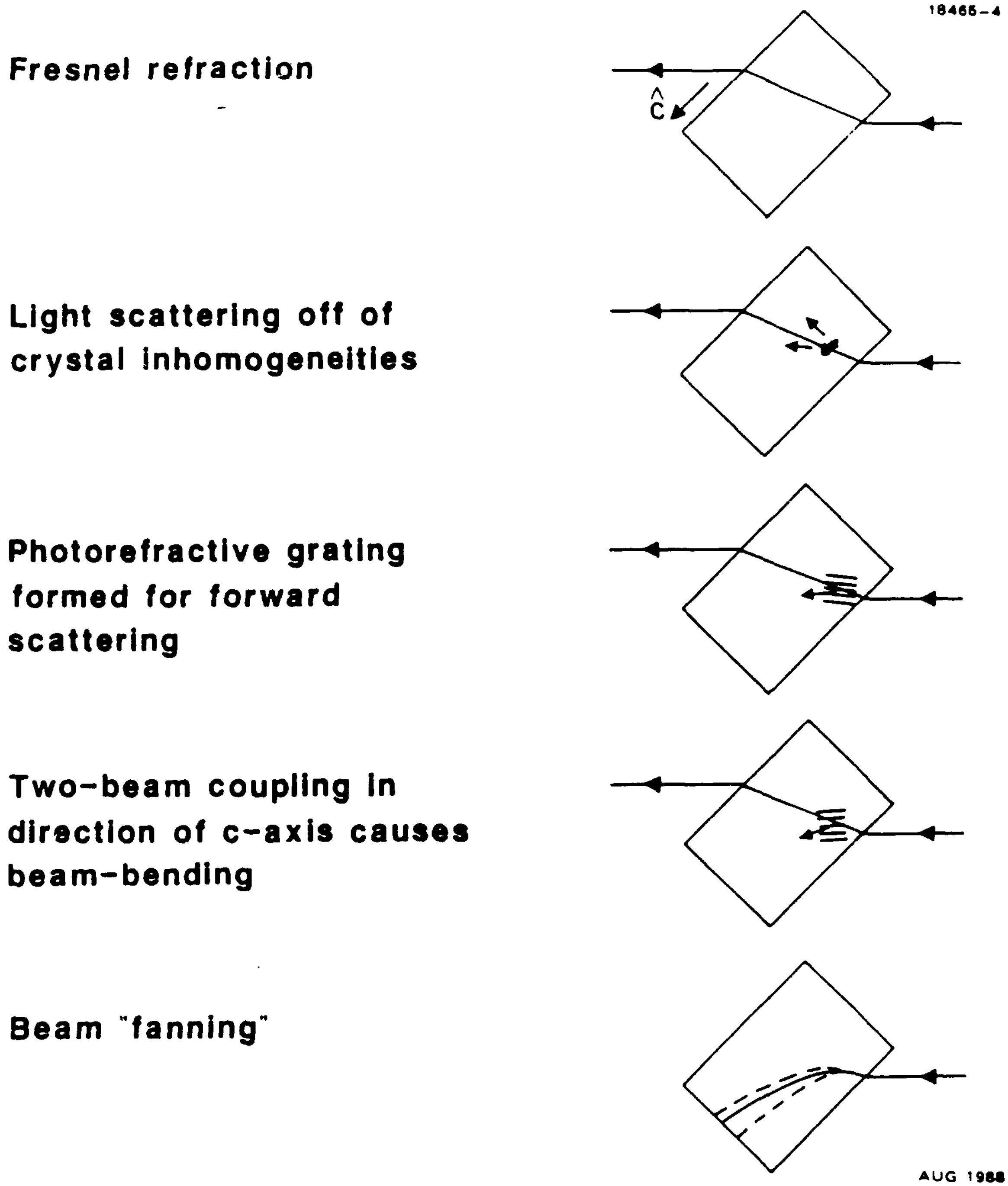

FIGURE 1. A physical picture for "beam-fanning" or forward stimulated photorefractive scattering (FSPS).

according to Snell's Law. A small amount of light then scatters off of some kind of inhomogeneity or residual grating in the crystal. The scattered light then interferes with the incident light to write a grating in the crystal. Initially, a large multiplicity of gratings are written by the mutual interference of the pump and the homogeneously scattered light. The strength of all these gratings varies widely both with their periodicity and their orientation. Gratings with a period exactly equal to a Debye screening radius create larger photorefractive space-charge fields than gratings of any other period. Those gratings oriented to take best advantage of the large anisotropy in $BaTiO_3$ electro-optic coefficients exhibit much higher diffraction efficiencies than gratings oriented in less-than-optimal directions. Thus, the laser beam is diffracted to the angle at which the forward gain is largest. Visually, the beam appears to "bend" or "fan."

If the crystal has a sufficiently large gain-length product above the BSPS threshold, then phase-conjugation via BSPS can be observed. BSPS develops according to the sequence illustrated in Figure 2. Some of the incoming light is scattered off of either crystal inhomogeneities, surface imperfections, or residual gratings in exactly the opposite direction to the forward-going light. The wavevector of the grating formed by the interference of the forward-going and the backward-scattered light will be oriented exactly parallel to the direction of the incoming beam. Light diffracted from this grating will propagate exactly backward, intensifying the field in the backward direction, increasing the fringe visibility and increasing the modulation depth of the index grating. Even more light is then diffracted in the backward direction, and so forth. The backward-scattered light is both coherent with the forward-going light, and is a phase-conjugate, just as in stimulated Brillouin scattering.

Just as for the other types of stimulated scattering, there is a threshold associated with BSPS; the threshold condition for the onset of BSPS was reported by Chang and Hellwarth[6] to be $\exp(\gamma l) \cong \exp(10)$ in order for the exactly backscattered intensity to be significantly larger than the intensity of randomly scattered light. This threshold condition has two subtle differences from that for the other types of stimulated scattering (for which $\exp[20] < \exp[gIl] < \exp[30]$). For SBS, the exponent depends on intensity, while for SPS, the gain is intensity-independent beyond the very low equivalent dark intensity (typically on the order of about 10 mW cm^{-2}). Thus, while in SBS the gain can always be increased by pumping the material harder (at least up to a level at which competing nonlinearities start to occur), this is not the case for SPS. The SPS gain depends only on the interaction length and on the gain coefficient γ. The SPS interaction length can be increased either by growing bigger crystals or by cascading available crystals in parallel, as shown in Figure 3. The gain coefficient can be optimized by either adiusting the angle of the beam with respect to the c-axis or growing a new crystal with a larger trap density. We found that, with our largest high gain crystal of immersed in index-matching fluid, it was just possible to observe BSPS without the use of external feedback loops.

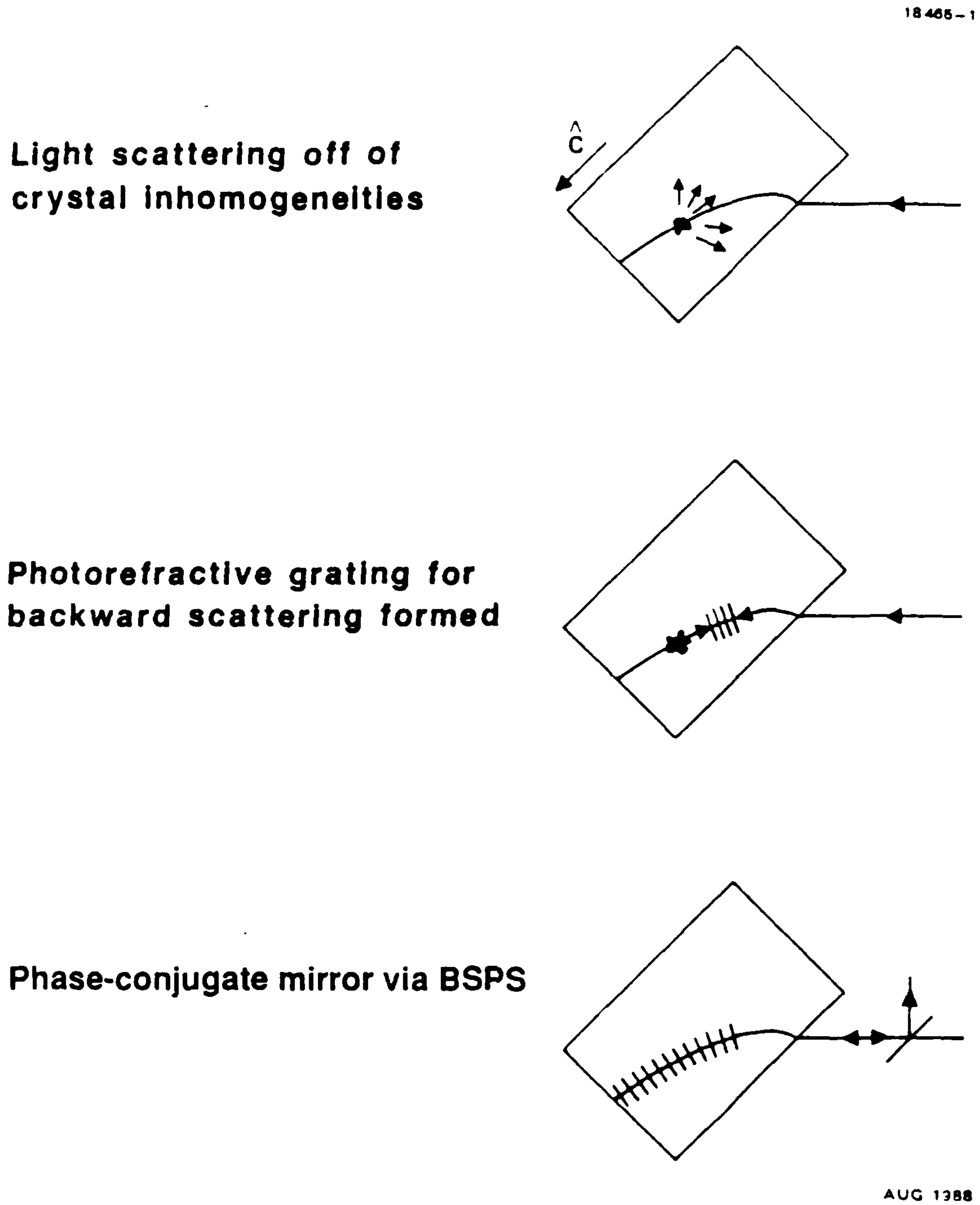

FIGURE 2. A physical picture for backward stimulated photorefractive scattering (BSPS).

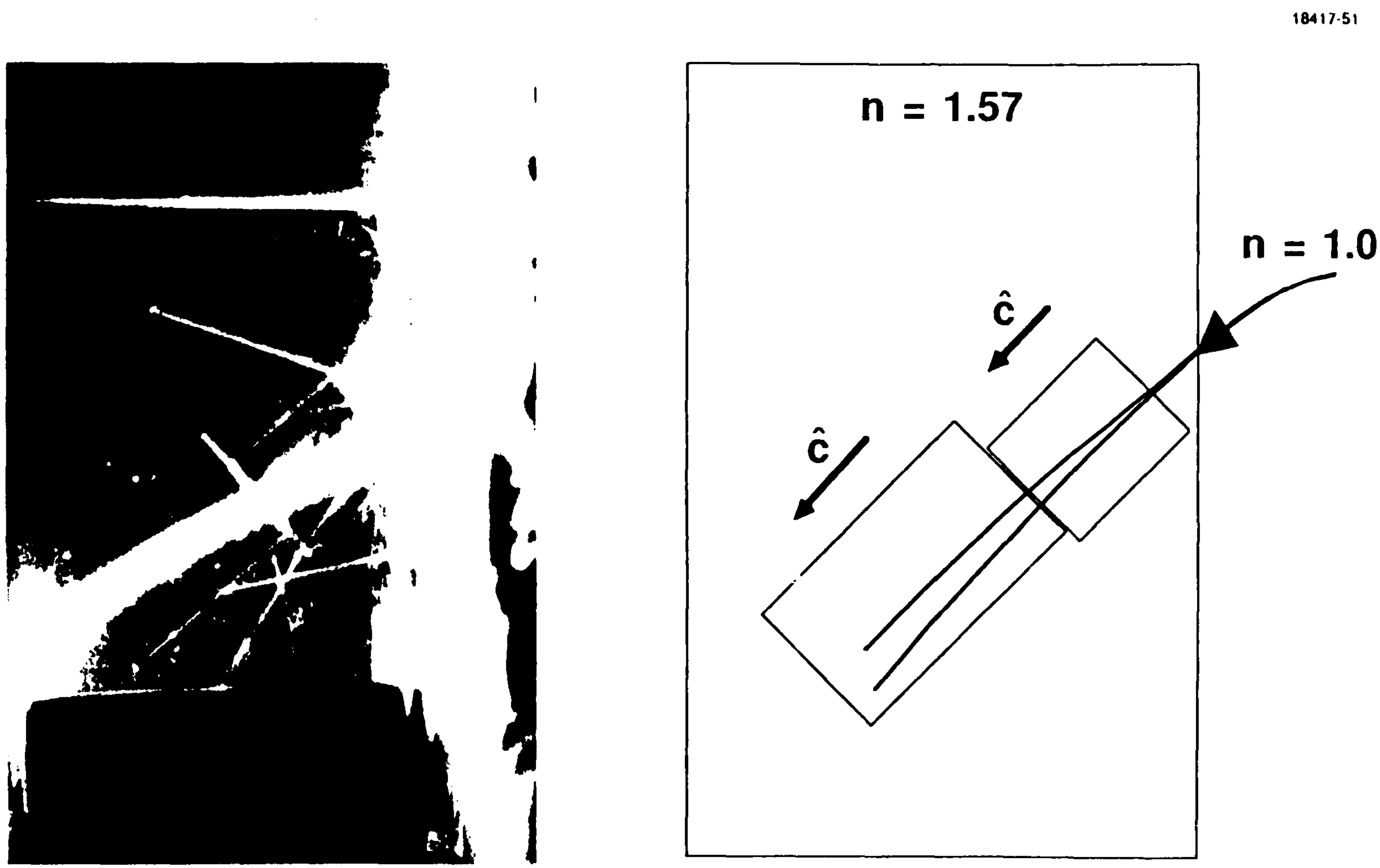

FIGURE 3. Two $BaTiO_3$ crystals cascaded in series to increase the BSPS interaction length.

2.1.2 Experimental Set-Up

The experimental set-up for our observation of BSPS is shown in Figure 4. Our best results were obtained with a crystal grown by Sanders and Associates (serial number 69K, 9.7 mm(c) X 7.0 mm by 6.1 mm dimension). P-polarized light was required for both FSPS and BSPS. Rotating the pump beam polarization to s caused the beam path inside the crystal to revert from its complicated filamentary pattern to the ordinary straight line propagation predicted by linear optics. Photographs of the beam path inside the crystal for both polarizations are shown in Figure 5. Figure 6 contains line drawings of the photographs' important features. BSPS without external feedback was seen only when the crystal was immersed in index-matching oil (n=1.57), and with the light entering an a-face of the crystal as shown.

2.1.3 BSPS Reflectivity and Stability Results

Since the gain-length product was only marginally above threshold, the reflectivity was smaller than is often obtainable with the TIR-conjugators. Depending on the alignment, intensity, and other experimental conditions, the reflectivity was either oscillatory with a peak value of 21%, or steady but with a low value of 3%.

Translating the crystal in the plane of the table (perpendicular to the direction of propagation of the pump) shortened the interaction length and eliminated the backward scattering, indicating that the BSPS was indeed very near threshold.

2.1.4 Effect of Diffuse White Paint

Chang and Hellwarth[6] reported that a glint of light scattering off a surface of the cuvette was found to assist with the onset of stimulated scattering. We tried to see if the BSPS reflectivity of our crystal could be improved by the deliberate introduction of scattered light. To obtain the largest diffusely scattered signal possible, we separately tried painting both the exit-face of the cuvette and the (+c)-face of the crystal with spots of white paint (brand name Liquid Paper), blocking the laser beam's exit from the cuvette. No enhancement of either the reflectivity or stability was observed (in either case), unlike in the work of Gunter et al.

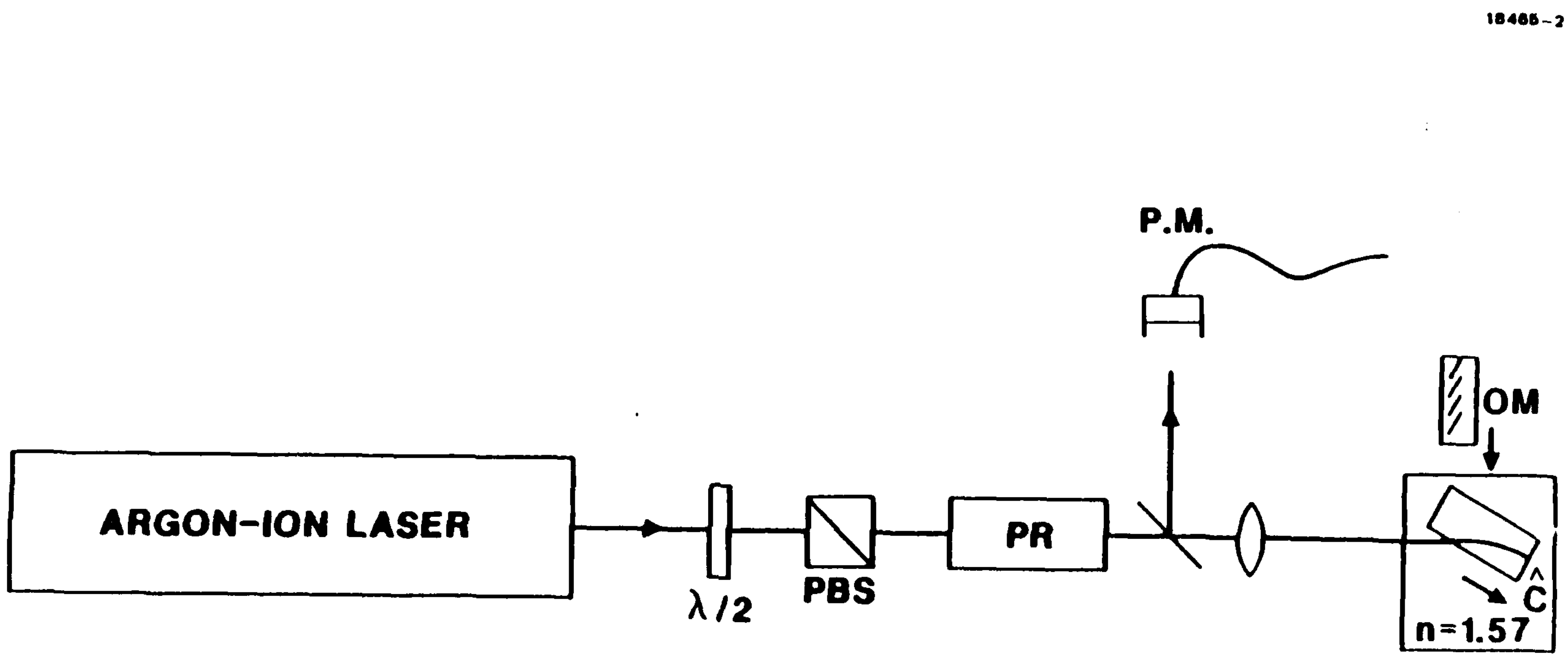

FIGURE 4. Experimental schematic for the observation of BSPS. The argon-ion laser first passes through a polarizing attenuator made up of a half-wave plate and a polarizing beamsplitter cube. The beam then passes through a polarization rotator able to provide both p-polarized and s-polarized light for the experiments. A 16 cm focal length lens then focuses the light near the crystal, which is oriented roughly as shown in a cuvette filled with index-matching fluid of n=1.57. For the beam-fanning and BSPS experiments, the polarization rotator PR is adjusted to obtain p-polarized light. The beam-fanning and BSPS is completely eliminated by rotating the polarization back to s. The crystal and its cuvette can be replaced with an ordinary mirror to obtain a calibration on 100% reflectivity, and the phase-conjugate return is sampled with a beamsplitter as shown and monitored with a power meter.

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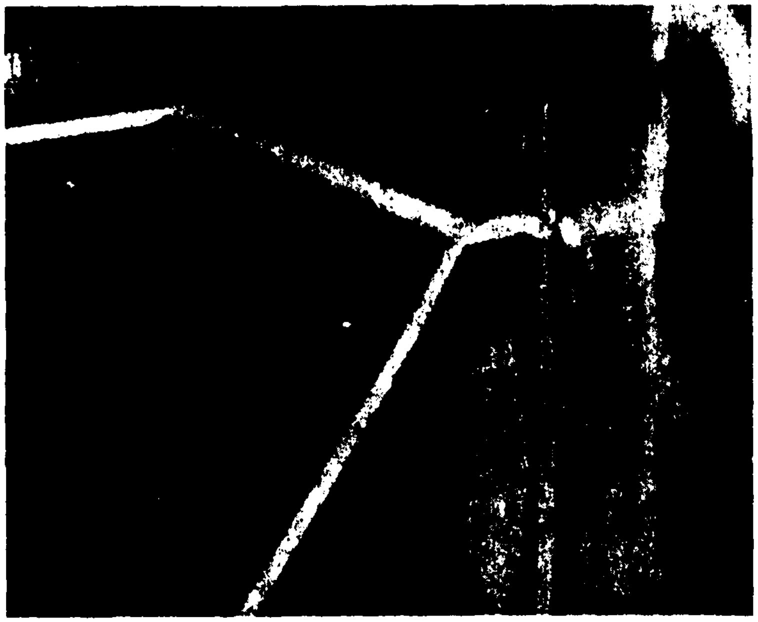
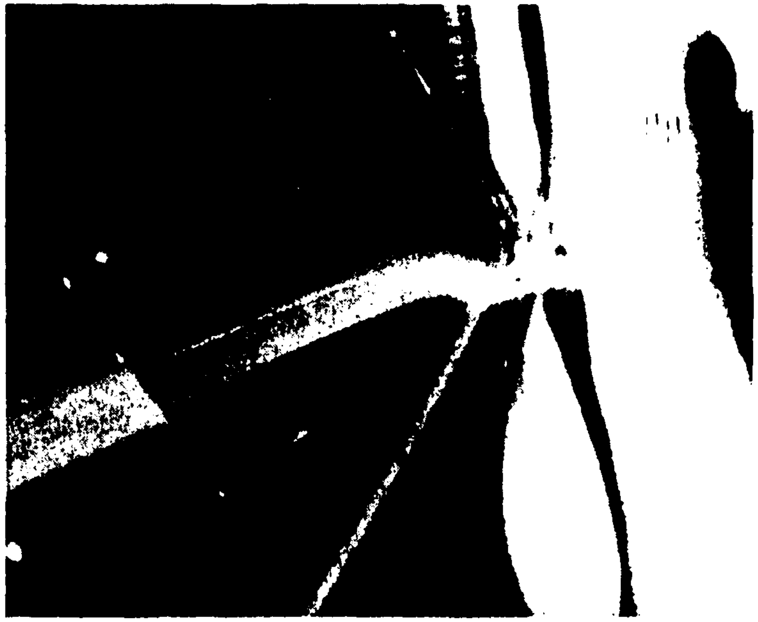


s-POLARIZATION
FRESNEL REFRACTION



p-POLARIZATION
BEAM-FANNING AND BSPS

FIGURE 5. Photographs of beam path in $BaTiO_3$ crystal during BSPS. Note fanning to angle of 13.2° with respect to the c-axis.

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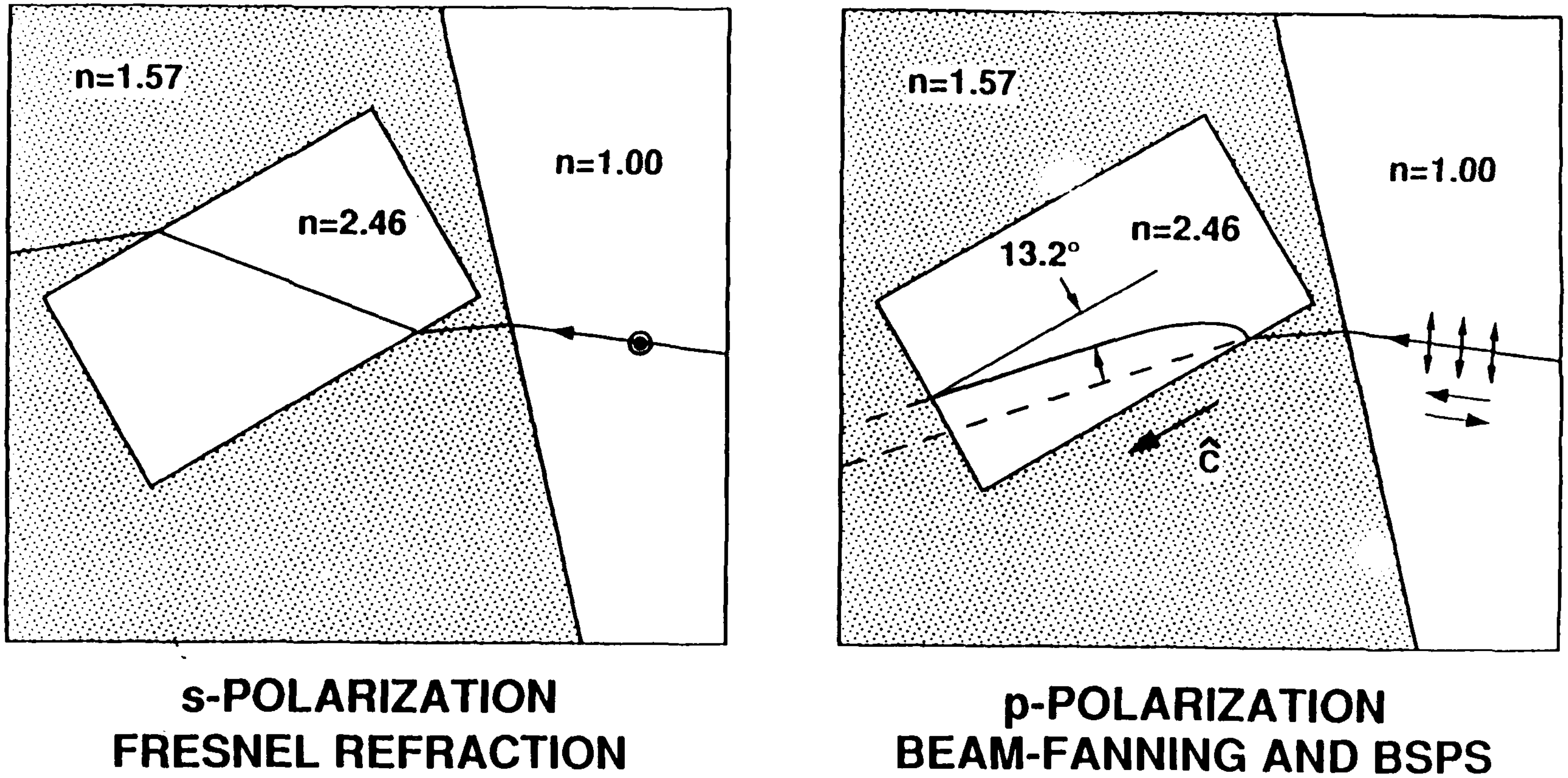

FIGURE 6. Line drawing showing main features of Figure 5.

2.2 FEEDBACK-ENHANCED BACKWARD STIMULATED PHOTOREFRACTIVE SCATTERING (FE-BSPS)

Having failed to improve either the reflectivity or stability with a perfectly diffuse scatterer, we tried several other feedback geometries that are well-known in the SBS literature for lowering the threshold for stimulated scattering. We recognized from our experience with SBS that not all kinds of feedback are helpful in improving the performance of self-pumped phase-conjugators. In particular, "print-through" problems that occur whenever the fed-back light is anything other than a perfect phase-conjugate or perfectly noisy can actually destroy phase-conjugate fidelity. Figures 7(a) and 7(c) illustrate two geometries designed to provide a phase-conjugate feedback signal. Figure 7(b) is a geometry that provides non-phase-conjugate feedback; as such it makes an interesting comparison for the other geometries. We refer to all those geometries that improved either the reflectivity or the stability of the conjugator as feedback-enhanced backward stimulated photorefractive scattering (FE-BSPS). With the geometry of Figure 7(a), the BSPS reflectivity was stable, while the loop geometries of Figures 7(c) and 8 both led to appreciably enhanced but so far unstable reflectivities. The results of our investigations to-date are summarized in Table I. Importantly, with this feedback, crystals which otherwise would be too short or have too small a backward gain to produce BSPS can be made to exhibit FE-BSPS.

2.2.1 Phase-Conjugate Seed, Separate Crystal, Linear Geometry

In Figure 7(a), the phase-conjugate seed is provided by a separate crystal that phase-conjugates via the total internal reflection mechanism discovered by Feinberg.[12] Initially, a separate, unaberrated pump beam was focused onto the TIR PCM to assist with the onset of its operation, but once the crystal orientation was optimized, the separate pump was no longer necessary and is consequently not shown in the figure.

In this case, the feedback stabilized the reflectivity at about 20%, a value comparable to the peak (but unsteady) reflectivity seen without feedback.

When a card was placed between the two crystals to block the seed, the signal decayed away with a time constant of 45 ms.

2.2.2 Non-Conjugate Seed Reflected from an Ordinary Mirror

Replacing the TIR-PCM described above with an ordinary mirror (OM), we found that the reflectivity of the system became unstable, oscillating periodically between about 11 and 21 percent.

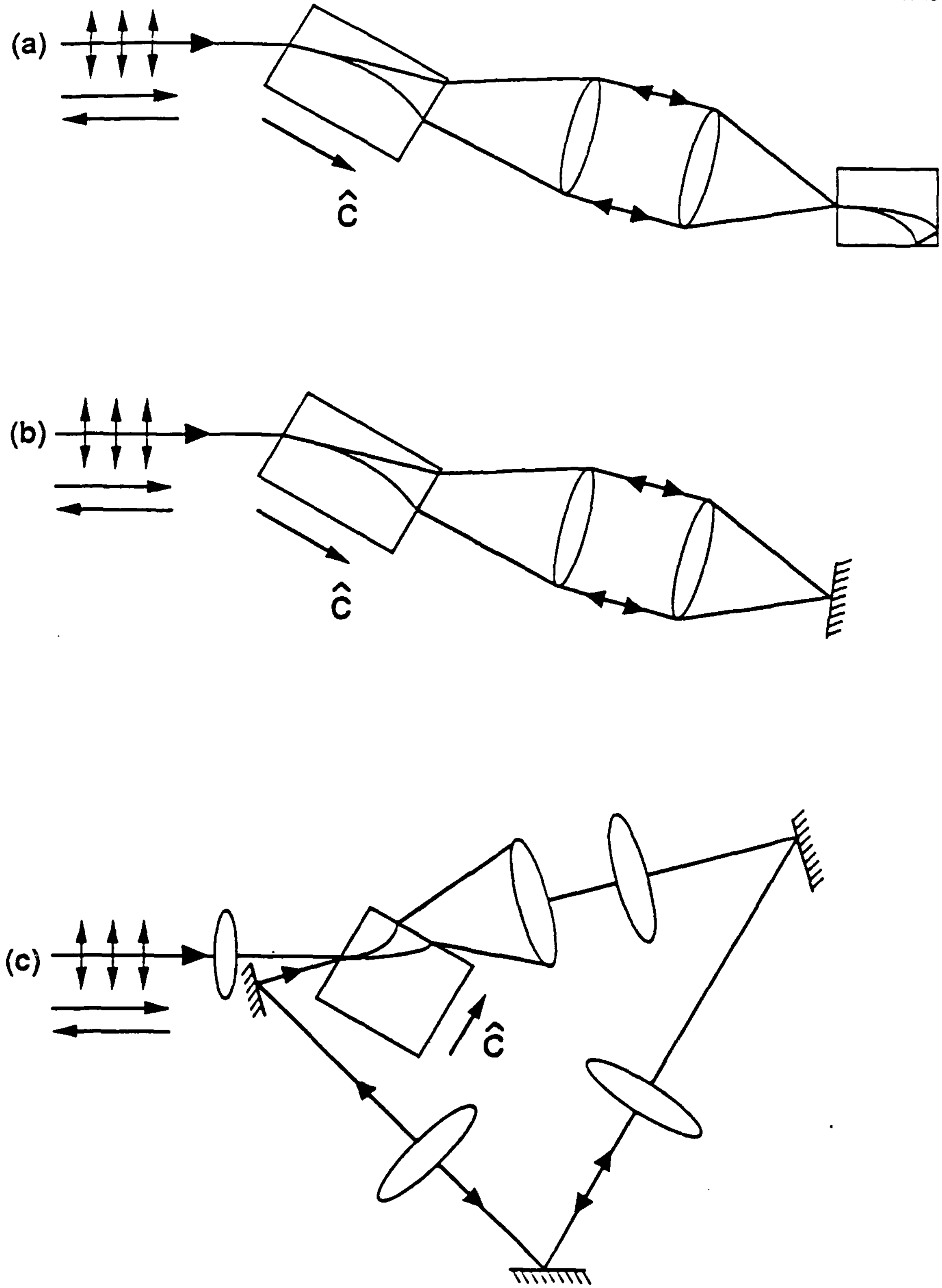

FIGURE 7. Three geometries studied for feedback-enhancement of stimulated photorefractive scattering. a) Using a separate crystal operating as a TIR-PCM to generate a phase-conjugate seed. b) Us. g an ordinary mirror (OM) to generate a non-phase-conjugate seed. c) Generating a phase-conjugate seed in the same crystal with a loop geometry.

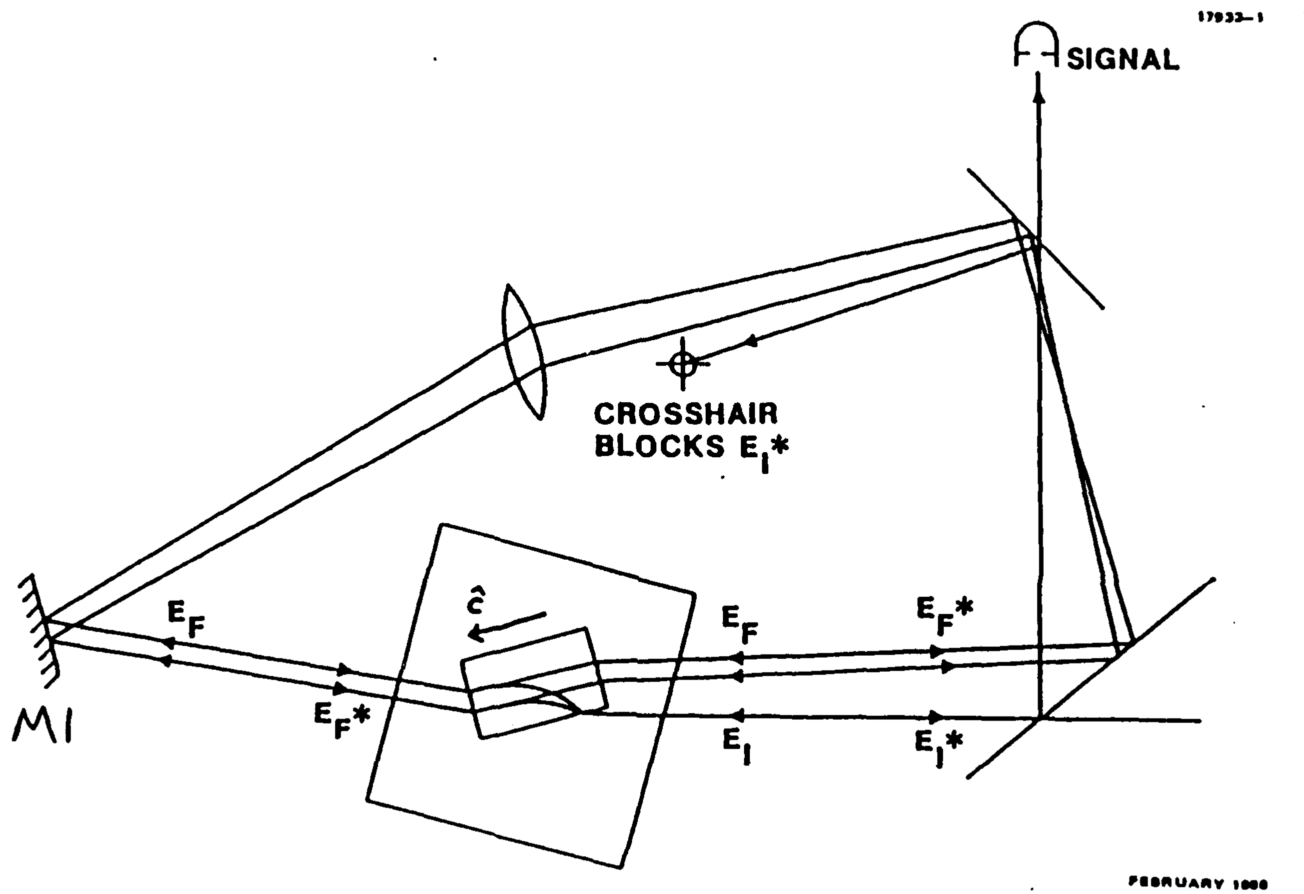

FIGURE 8. Our first implementation of the ring-FE-BSPS concept. In this implementation, a very small angle between the fed-back light and the pump can be obtained by using a beamsplitter and adjusting the alignment so that the fed-back light and the pump are nearly superimposed on each other at the beamsplitter's surface. The conjugate of the pump can be prevented from circulating around the loop by the insertion of a cross-hair, as shown.

TABLE I. Preliminary results on the comparative reflectivities and response times of the BSPS and FE-BSPS phase-conjugators discussed in this report.

	R	τ (ms)	Comment
WITHOUT FEEDBACK			
• one crystal	~3%	N/A	steady
	21% peak		unsteady
• two crystals in series	26% peak	N/A	unsteady
WITH FEEDBACK			
• OM	(16±5)%	60	oscillations
• PCM in separate crystal	19.3%	45	steady
• PCM in same crystal (ring)	96%	?	oscillations
• diffuse scatterer (white-paint)	1 to 3%	N/A	steady

When a card was placed between the two crystals to block the seed, the signal decayed away with a time constant of 60 ms.

While it would be easy to understand why the "print-through" problems alluded to above would degrade the fidelity of 7(b) (the OM seed, a non-conjugate) as compared to 7(a) (the TIR-PCM seed, a phase-conjugate), it is harder to understand how the conjugate or non-conjugate nature of the seed might impact the response time and stability performance associated with the system dynamics. Noting that the TIR-PCM seed automatically and precisely lines-up the filaments with themselves for retraversal of the crystal suggests that the relatively unsteady behavior of the OM-seeded system might be associated with the misregistration of the filaments on their return path through the crystal, and the resulting inter-filamentary competition that might be expected to occur as a consequence.

2.2.3 Phase-Conjugate Seed, Same Crystal, Ring Geometry

The ring-FE-BSPS geometry shown in Figures 7(c) and 8 has exhibited even higher reflectivities and offers the additional advantage that it requires only one crystal. An implementation of this ring geometry not requiring index-matching fluid, shown in Figure 7(c), was implemented with a crystal that was too short to exhibit BSPS without external feedback (Sanders and Associates sample 69F, having dimensions 6.20 mm(c) by 6.87 mm by 5.52 mm). Following the beam path around the loop in the figure, we see that the incoming light refracts into an a-face of the crystal, then fans towards the c-axis before exiting the (+c)-face of the crystal. The now widely diverging, fanned light, labeled E_F, is captured by a series of lenses and mirrors and refocussed into either the entrance or the front face of the crystal at a very small angle with respect to the c-axis. A phase-conjugate E_F^* of this fanned light is generated in the crystal, possibly via BSPS-assisted four-wave mixing. E_F^* then propagates back around the loop (counterclockwise in the figures) and exactly retraces the complicated filamentary path of the forward-going, fanning light in the crystal. This stimulates the generation of more backward-scattered light, dramatically lowering the threshold for BSPS and greatly enhancing the phase-conjugate reflectivity.

In this case, the reflectivity was found to oscillate sinusoidally between about 22 and 44% with a 1.4 Hz frequency for 99 mW of incident power.

To better facilitate the alignment of the fed-back light E_F at a very small angle with respect to the pump E_I at the (-c)-face of the crystal, we implemented the geometry shown in Figure 8. In this implementation, obtaining a very small angle between E_F and E_I is accommodated by the use of a beamsplitter (the fed-back light and the pump are nearly coincident on the beamsplitter's surface). The conjugate of the pump can be prevented from circulating around the loop by the

insertion of a cross-hair, as shown. Preliminary measurements of the reflectivity of this system indicate that the reflectivity can be very high, exhibiting transient peaks perhaps as high as 96%, but that these high reflectivities are so far not stable.

In Figure 8, the cross-hair CH blocks the circulation of the input (pump) beam's conjugate E_I^* counterclockwise around the loop, thus preventing a potential "print-through" problem that can occur if a non-conjugate seed were fed back into E_F (E_I^*, fed back into the (+)c-face of the crystal, is not a conjugate of E_I inside the crystal).

In the configuration shown in Figure 8 (using index-matching oil), the phase-conjugate reflectivity was observed to increase from just a few percent to nearly 100%. Irregular oscillations in the intensity of the phase-conjugate signal occurred, and their frequency seemed to increase with increasing intensity. The placement of the cross-hair CH in the loop as described above was expected to cause an increase in the reflectivity since it blocks E_I^* (which is not a conjugate of E_F) from reentering the +c face of the crystal.

Both configurations share the important common feature that E_F^*, generated by noise-seeded four-wave mixing, exactly retraces the path of the fanned beam E_F throughout the length of the crystal. The phase-conjugation of the fanned beam thus results in self-aligning pumps that are phase-conjugates of one another and are exactly counter-propagating over the very complicated, filamentary beam path in the crystal.

In both these demonstrations, a p-polarized argon-ion laser beam was first directed into a $BaTiO_3$ crystal in such a way that, once the beam fanned, it propagated through the rest of the crystal at or near the angle for maximum backward gain. If the gain-length product for the crystal is long enough, and if the fanned light is sufficiently far away from the corner to prevent TIR-conjugation from occurring, then a phase-conjugate signal builds up via ordinary BSPS, even if the external loop is blocked to prevent the circulation of the fanned light around the feedback loop.

When the feedback loop is unblocked, the fanned light E_F transmitted through the (+)c face of the crystal is collected with a series of lenses and other optics as shown, and redirected [clockwise in Figures 7(c) and 8] back around into the entrance face of the crystal.

The coherence length of the laser is (and probably must be) much longer than the length of the loop.

2.2.4 Comparison of FE-BSPS with Other Photorefractive Conjugators

FE-BSPS has several advantages over other types of photorefractive phase-conjugators, such as four-wave mixing conjugators, self-pumped phase-conjugate mirrors utilizing total

internal reflection (TIR-PCMs, frequently referred to as "cat-conjugators")[12] and BSPS conjugators without feedback.

FE-BSPS shares with ordinary BSPS and TIR-PCMs the important advantage over four-wave mixing that externally generated plane-wave pumps are not required.

As compared to self-pumped conjugators utilizing total internal reflection,[12] FE-BSPS shows good potential for scaling to larger input beam diameters. In particular, for a crystal of fixed size, the largest beam diameter that can be accommodated by the FE-BSPS conjugator should only be limited by the size of the crystal's c-face, since it should be possible to arrange for the beam to use these faces both for entering and exiting the crystal. By contrast, the maximum beam diameter that can be accommodated by the TIR-conjugator is limited not only by the size of the c-face, but also by the size of the other face which it must reflect from in one of the corners. The maximum beam size that can be accommodated by the TIR-conjugator is further limited by geometrical constraints imposed by the internal loop. By contrast, in the FE-BSPS geometry, external optics can be used to feedback the light, thus leaving more freedom to adjust the crystal position and angle to optimize the backward gain.

In the TIR-conjugator, since the feedback loops are all inside the nonlinear medium, light circulating around the loop may experience some gain, but it must also experience both absorption and two-beam coupling losses as it circulates around the loop. By contrast, with an external loop as used in the ring-FE-BSPS, the losses are mainly limited by the f-number of the collection optics and the quality of AR coatings. Fresnel losses at the crystal-air or crystal-oil interfaces can be eliminated by AR coatings on the crystal surfaces.

Unlike the TIR-conjugator, no internal reflections are required in the ring-FE-BSPS geometry. Since the damage thresholds of surfaces are typically smaller than bulk damage thresholds, higher-average-power damage thresholds should consequently be expected from the ring-FE-BSPS device.

In addition, longer interaction lengths should be obtainable for a given crystal size with the FE-BSPS geometries, since nearly the whole crystal length can be used for backward scattering. By contrast, much of the crystal length in the TIR-PCM geometry is used to create the feedback loop.

The advantage of the ring-FE-BSPS geometry described in this disclosure over the external feedback loop in Cronin-Golomb et al.[14] is more subtle. In the ring-FE-BSPS geometry described above, the light is fed back into the front face of the crystal at a very small angle with respect to the pump, minimizing the forward gain, and strongly favoring backward scattering. The backward scattering is a more desirable coupling mechanism than forward scattering for several reasons. First, the interaction length of backward scattering is limited only by the crystal size and the crystal's absorption length, whereas the interaction length for forward scattering can

be much smaller than this, and drops as the angle between the beams increases. Second, for the typical $BaTiO_3$ crystal in which the Debye screening length is larger than either the electron or hole ranges, the backward (small period) gratings have faster response times than the forward (large period) gratings.[17]

Finally, FE-BSPS exhibits greatly enhanced reflectivities over BSPS without feedback. Lower thresholds and better phase-conjugate fidelity are also expected.

2.3 STABILIZATION

The fact that FE-BSPS systems can be stable is evident from the stable reflectivity exhibited by the linear implementation [Figure 7(a)]. However, the high reflectivities observed with the ring-FE-BSPS geometry will have to be stabilized before its application to any practical system can be envisaged. The observed stability of the linear-FE-BSPS geometry indicates that the general concept of FE-BSPS can lead to stable outputs.

One theoretical paper indicates that generic ring feedback geometries are inherently unstable,[18] but there are several very detailed experimental investigations in the literature mapping out the stability conditions for TIR-PCMs, which also involve a feedback loop. It is evident from the data of one of these studies[19] that, at least for the TIR-PCM, the stability is sensitively dependent on the separation between the crystal and the lens that focuses the beam into the crystal. We expect to find an analogous stability condition for our ring-FE-BSPS PCM.

Furthermore, Gunter et al.[10] have reported that the stability of BSPS can be affected by both the nature of the feedback and the optical intensity.

While SPS frequency shifts are known to be small,[20] data of Nowak et al.[19] indicate that a correlation exists between changes in the frequency shift and the observed pulsations in the TIR-PCM. According to Lam,[5] these frequency shifts arise from the photovoltaic properties of $BaTiO_3$ and depend on the optical intensity.

Whatever the source or magnitude of the SPS frequency shift, our FE-BSPS geometries offer the important advantage that they can provide the correct frequency shift required for stable operation. Crystal-to-crystal variations in frequency shift, for example, might be eliminated by biasing individual crystals with the appropriate level of incoherent illumination. As described above, the PCM-seeded linear-FE-BSPS appears to be stable even without any special biasing to obtain the appropriate frequency shift.

2.4 FIDELITY

Extensive evidence from the SBS literature indicates that the TIR PCM-seeded and the ring-seeded FE-BSPS conjugators should both exhibit excellent phase-conjugate fidelity.

Similar feedback enhancement geometries utilizing electrostrictive acoustic gratings[21-25] and stimulated Brillouin scattering (SBS)* rather than photorefractive gratings have been proposed and demonstrated in bulk media,[22-24] in "lightpipes,"[21] and in single-mode optical fibers.[25]

Our experiments have qualitatively verified that the BSPS and FE-BSPS conjugator geometries discussed above all exhibit qualitatively good fidelity. They were certainly very effective at correcting for the very severe and nonlinear beam-fanning aberration of the $BaTiO_3$ crystal. They also appeared to correct well for the phase aberrations of an HF-etched glass aberrator. Even in the presence of both of these aberrators, the returned near-field beam profile in the absence and presence of a phase aberrator was nearly identical to the beam profile formed by reflection from an ordinary mirror without any aberrators.

We are planning to complement these qualitative diagnostics with computerized video far-field intensity contour plots and Strehl ratio measurements to compare the relative fidelities of the various geometries discussed above with the fidelity of the TIR-PCM conjugator.

2.5 INTER-FILAMENT AND INTER-CRYSTAL CROSS-TALK REQUIREMENTS

Several experiments in the literature, such as Valley et al.,[11] have experimentally demonstrated that good fidelity in stimulated Brillouin scattering is critically dependent on obtaining good mutual overlap of all parts of the beam. This concept is of special interest to the fidelity of BSPS in the presence of piston errors. A simple example of this potential problem is illustrated in Figure 9. Two rays representing two separate pixel-elements of a single beam are drawn. One ray picks up a piston-error with respect to another, as drawn, just as it might if it were to have passed through an amplifer with a different thickness than the adjacent ray. If the simple picture of BSPS described above is accurate, each of the two rays would propagate

* Despite the proven fidelity of Brillouin conjugators, photorefractive conjugators are preferred for cw applications because they require much lower powers (on the order of milliwatts per square centimeter), as compared to the high peak pulsed power requirements to form the electrostrictive gratings mediating SBS. The peak power level in Odintsov and Rogacheva,[21] for example, was 1.8 MW. Furthermore, phase-conjugate beams generated via SBS are always frequency-shifted (by the Stokes frequency, several gigahertz) whereas SPS (and FE-BSPS) signals have relatively negligible frequency shifts on the order of a few hertz. Finally, the SBS ring geometry with submilliwatt pump threshold demonstrated by Stokes et al.[23] has a very large frequency shift (34.2 GHz) and cannot conjugate a complicated spatial image since it is uses a single-mode fiber.

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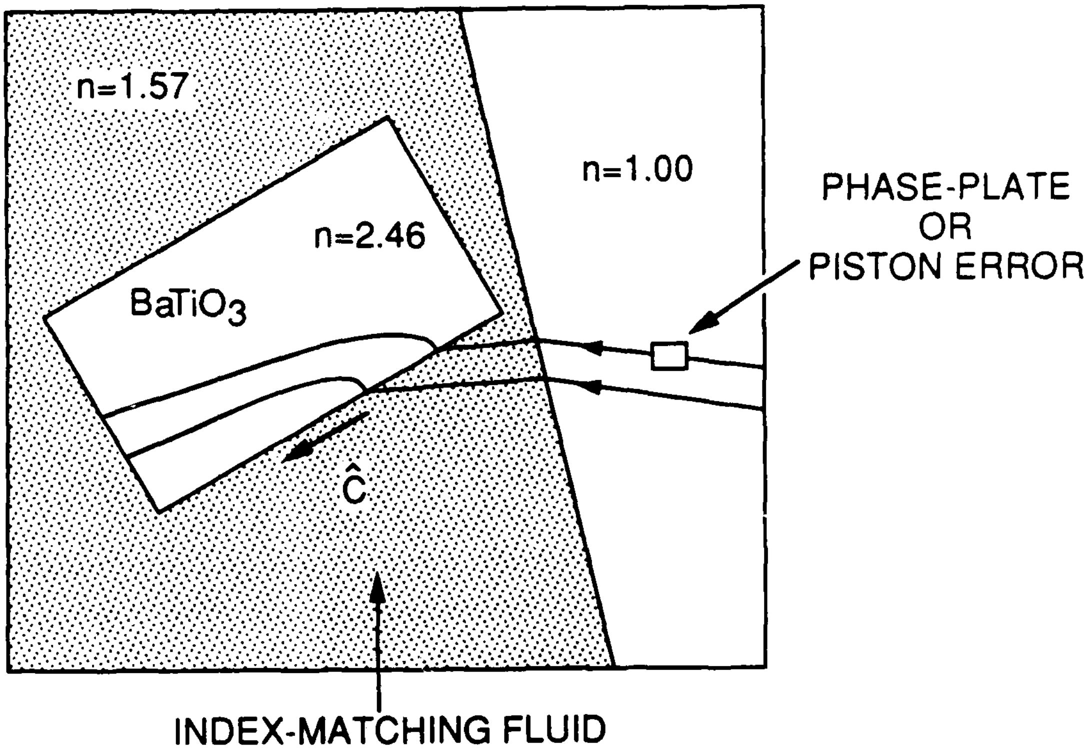

FIGURE 9. A potential cross-talk problem arising from a Piston-Error.

separately through the crystal, without much cross-talk. If there were no cross-talk between adjacent "pixels" in a mosaic beam pattern, then the piston-error correction capability would be poor. In actual fact, the following two possible sources for the necessary cross-talk can be hypothesized: diffraction and forward scattering. Diffractive cross-talk may be minimal for low spatial frequency aberrations such as piston error; the insertion of a higher spatial frequency aberration may improve the piston-error correction capabilities for BSPS. Forward scattering (a.k.a. beam-fanning or BSPS) might be more effective at producing good cross-talk.

The fact that we were unable to obtain BSPS entering the (-)c-face of the crystal may be evidence of the important cross-talk role played by beam-fanning in the generation of a phase-conjugate wave. One would not necessarily expect to obtain good cross-talk between nearest-neighbor or more distant "tiles" of a mosaic beam.

The ring-FE-BSPS geometry provides an obvious mechanism for inter-filament or crystal-to-crystal crosstalk, as shown in Figure 10.

2.6 CONCLUSION

Already on this program, we have observed a previously rare phenomena--backward stimulated photorefractive scattering (BSPS) without feedback. Only one of many available crystals had a sufficiently long gain-length product to exhibit this effect without the use of feedback. High-resolution photographs of the light-scattering patterns inside the crystal during BSPS show the break-up of the beam into complicated filamentary patterns. The stronger filaments straighten out to an angle of 13.2° with respect to the c-axis. The measured reflectivity from this conjugator was variously either very low (≅3%) or higher (having transient peaks of about 20% reflectivity) but unstable.

Feedback-enhanced BSPS (FE-BSPS), a means to enhance or stabilize the BSPS reflectivity, was invented by applying a proven SBS threshold-reduction concept to the reduction of the SPS threshold. This concept involved injecting a phase-conjugate seed into the exit (+c) face of a $BaTiO_3$ crystal oriented for the maximum possible backward gain. In one implementation of this concept, a separate crystal (operating as a conventional TIR-PCM conjugator) was used to generate the conjugate seed. A second implementation requiring only one crystal used a ring geometry to create and back-inject the phase-conjugate seed.

Preliminary characterization of the reflectivities and fidelities of BSPS and FE-BSPS systems is promising. The fidelities are at least qualitatively good, high reflectivities have been seen, and stable operation of one FE-BSPS geometry has been achieved.

Inter-filament and inter-crystal cross-talk has been identified as a key requirement for the scaling of BSPS and FE-BSPS to large-area laser diode arrays. A concept for comparing the

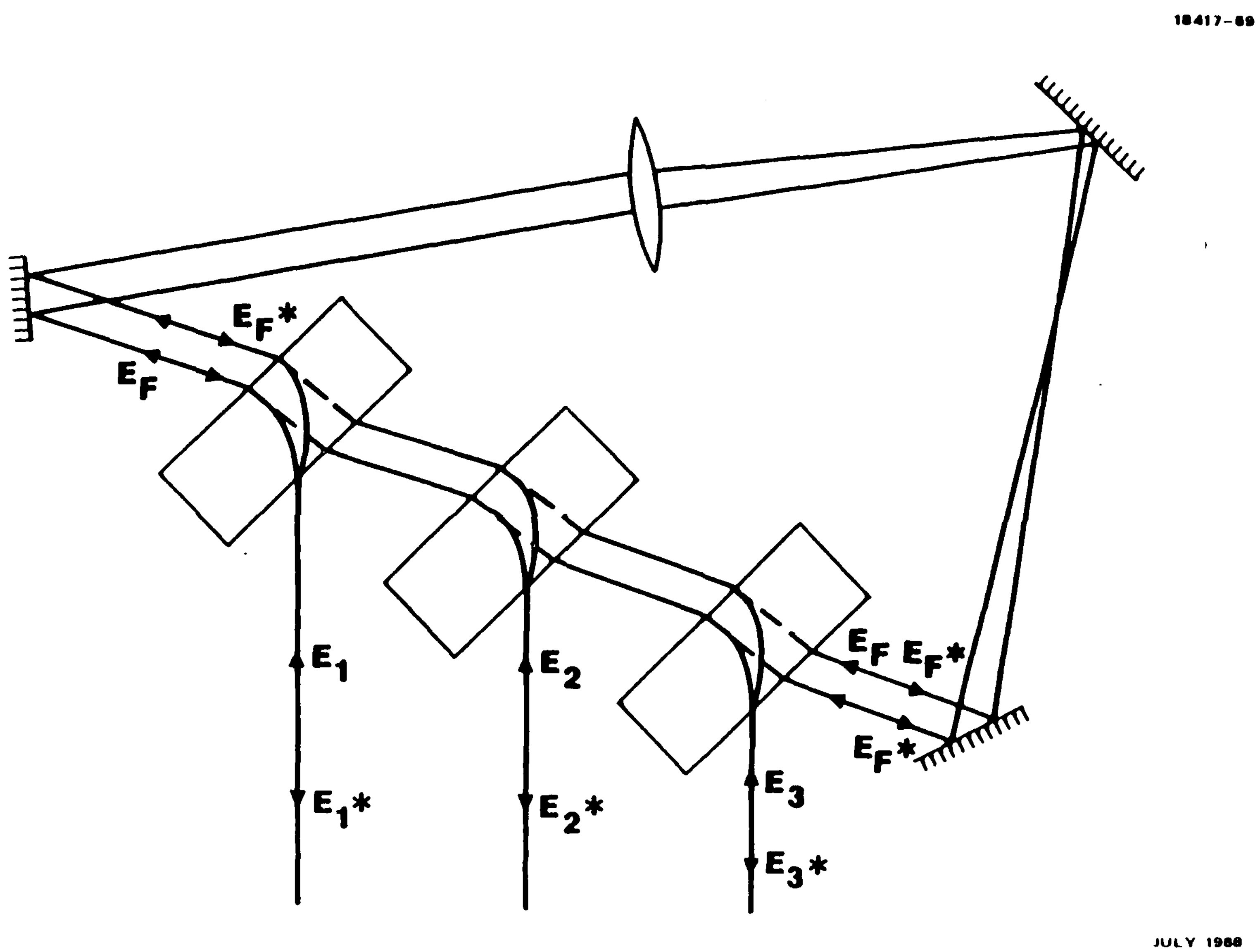

FIGURE 10. Scheme to utilize the ring-FE-BSPS geometry to assure goo d inter-filament and inter-crystal cross-talk for the phase-conjugation of large area beams.

effectiveness of this cross-talk in the various BSPS and FE-BSPS geometries at correcting for piston-error aberrations is discusssed.

In the remaining six months of the contract, we shall try to optimize the reflectivities, stabilities, and fidelities of the FE-BSPS geometries discussed above.

SECTION 3

SELF-PUMPED CONJUGATION IN GALLIUM ARSENIDE

3.1 INTRODUCTION

Recently, much attention has been given to the use of semiconductor materials for phase conjugation and image processing,[26] two-wave mixing,[27] and optical bistablity for logic operations.[28] Semiconductors as candidate nonlinear media for phase-conjugators offer several potential advantages over $BaTiO_3$, including faster response times (microsecond to picosecond), convenient wavelength matching to potential semiconductor laser lines, suitability for optical-fiber-based communication links, and integrability with optical systems in monolithic structures. Moreover, operating temperature range as well as optical damage threshold of these materials are expected to be greater than those of certain ferroelectric oxides.

Phase-conjugation has been demonstrated in these materials using the conventional externally pumped four-wave mixing geometries,[26] but self-pumped phase-conjugation in semiconductors has yet to be reported. Recently, large two-wave photorefractive gains in bulk GaAs and InP have been reported. Gains in the range of 1 to 6 cm^{-1} have been measured in these nonlinear media,[29-31] indicating that self-pumped operation should be achievable under the proper operating conditions. In the two-wave mixing measurements reported in the literature, two techniques were employed to yield the above-mentioned high gains: (1) moving grating experiments,[29] employing frequency-shifted beams in the presence of static external fields; and (2) stationary grating experiments,[30,31] with the application of ac fields (sine waves and square waves) across the crystal. The fields employed were on the order of 10 kV cm^{-1}. These techniques are required to maximize the internal space charge fields, thereby resulting in efficient energy exchange (i.e., two-wave gain) of the interacting optical beams.

3.2 PROGRESS

Given the existence of such large two-wave gains in these materials, we are measuring and optimizing the gain of our nonlinear medium and constructing an apparatus that should be capable of realizing self-pumped phase conjugation. For our initial experiments, we have chosen GaAs as the nonlinear medium. The optical source is a single longitudinal and transverse mode diode-pumped Nd:YAG laser at 1.06 µm. Several different self-pumped conjugation geometries[14] are being employed in our experiments: the so-called external loop configuration, as shown in Figure 11; and the bidirectional linear resonator, shown in Figure 12. Both

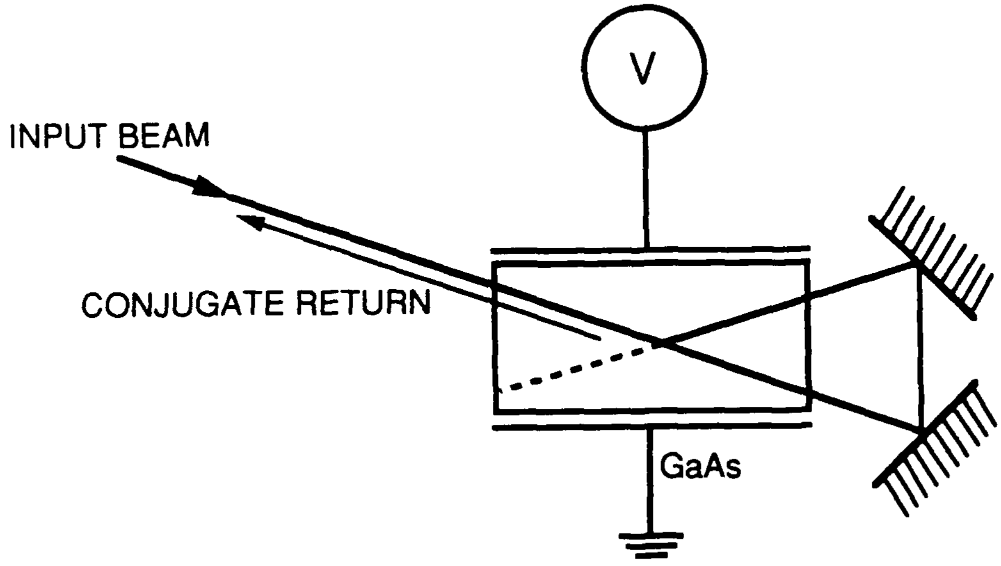

FIGURE 11. Self-pumped geometry using an "external loop" configuration.

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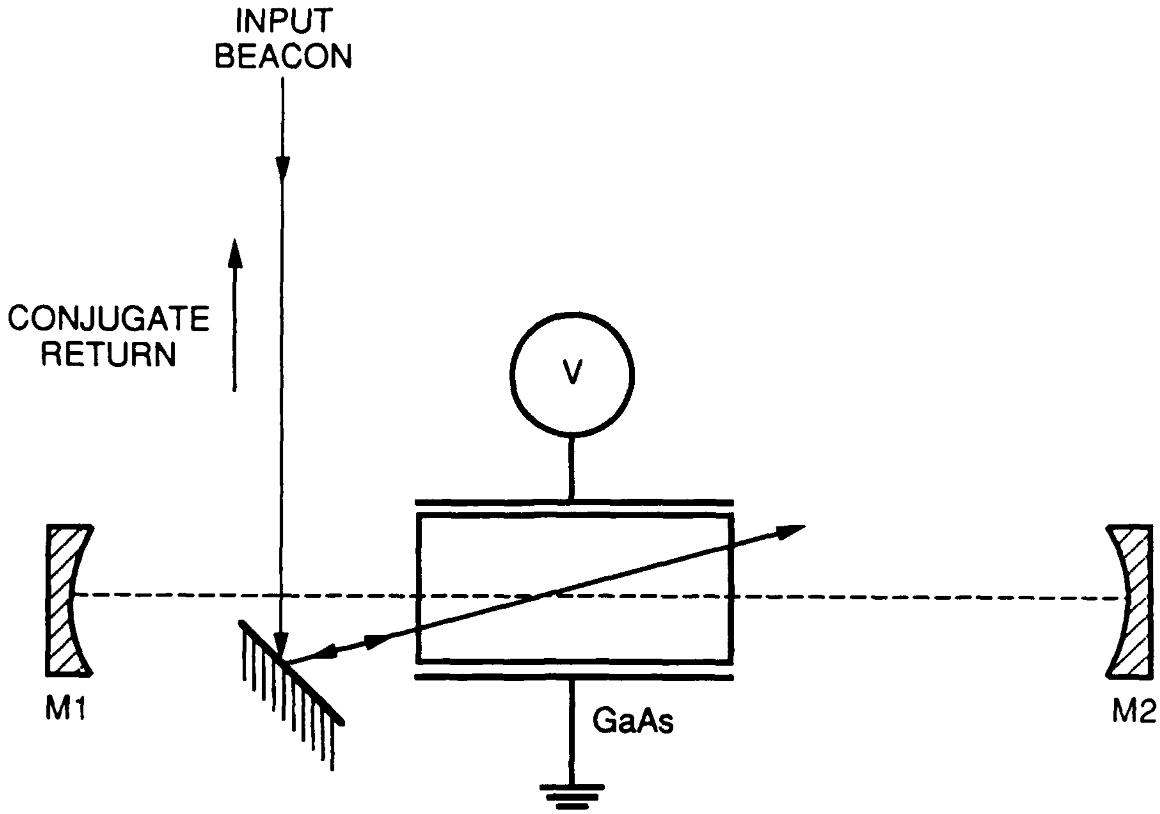
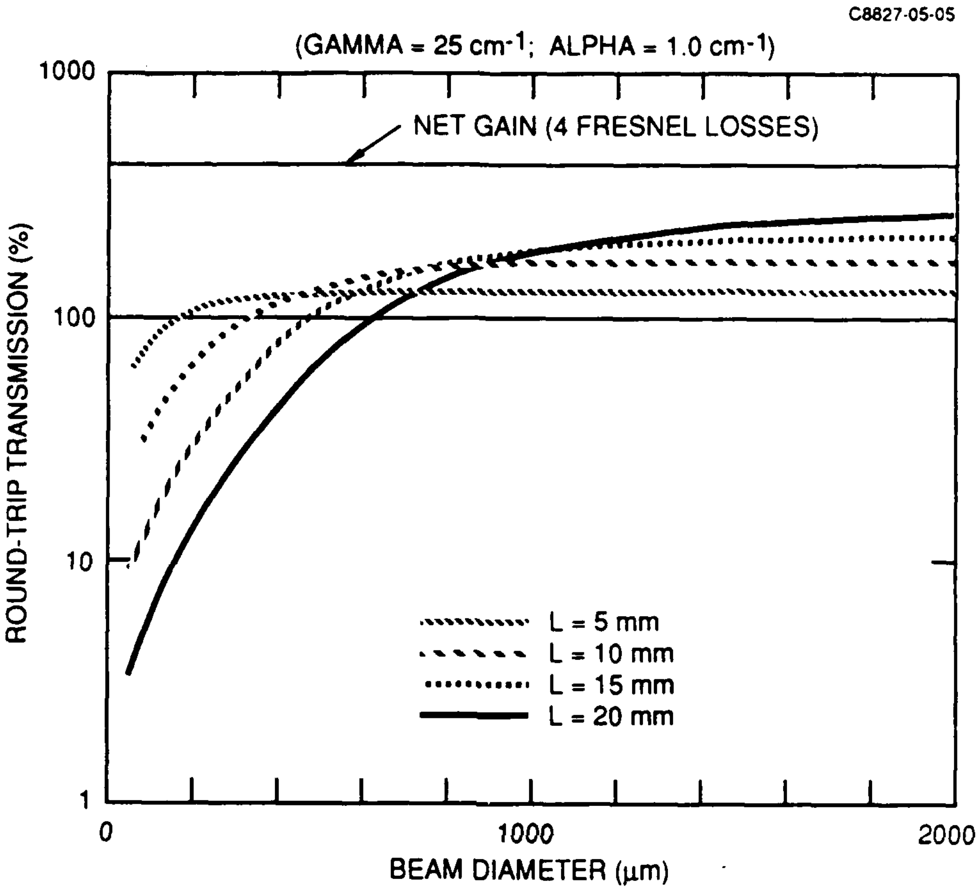


FIGURE 12. Self-pumped geometry using a bidirectional linear resonator.

geometries have been previously exploited for use in self-pumped conjugation experiments involving such materials as $BaTiO_3$ (a photorefractive medium),[14] CS_2 (a Brillouin-active medium),[32] and atomic sodium (a resonantly enhanced vapor).[33] In all these examples, conjugation proceeds via a combination of nonlinear optical interactions involving two-wave mixing as well as dynamic grating formation and readout (i.e., four-wave mixing).

Using existing GaAs samples in our laboratory, we measured two-wave gains up to 3 cm^{-1} with an applied ac square wave voltage of 6.4 kV (peak-to-peak) at a frequency of 20 kHz across our 4 mm crystal. This value is consistent with those reported in the literature[30] under similar operating conditions. We also measured the phase-conjugate reflectivity using a standard externally pumped four-wave mixing geometry with this crystal under the same applied field conditions. The measured reflectivity (≈13%) is also in agreement with previous results. We next employed a four-wave mixing geometry using a single pump beam; the counterpropagating pump was derived by reflecting the residual transmitted beam through the sample back into the crystal. This geometry approximates that of the bidirectional resonator; for this configuration, a reflectivity of ≈1% was measured. This value is not unreasonable, given the linear losses (absorption [73%] and two Fresnel reflections [2x30%]) of the forward-going pump through the sample, yielding a backward pump with an intensity equal to 18% that of the forward-going beam. Another factor contributing to a lower reflectivity is an imperfect polish of the crystal faces (several waves across the surface), which resulted in a transmitted pump beam with an appreciable degree of distortion. We have since repolished the samples to better than $\lambda/10$ of distortion across the crystal faces. A sample of improved optical quality will result in the formation of well-defined gratings, thereby enabling better control of the optimum grating period necessary to achieve the highest two-wave gain and hence, the largest possible phase-conjugate reflectivity.

To gain additional insight into the self-pumped conjugator using the configuration shown in Figure 12, we calculated the round-trip transmission of a resonator mode within a symmetric cavity containing a GaAs two-wave gain medium (with off-axis pumping). The external off-axis angle for this calculation (≈4°) was chosen to result in a grating period (≈15 μm) that optimizes the two-wave gain in the crystal.[31] This calculation basically corresponds to an oscillation or threshold condition for conjugation; the useful conjugate output, which actually is a cavity loss, has been neglected for this calculation. Input parameters for this calculation are the two-wave gain coefficient (2.5 cm^{-1}), linear loss (1.0 cm^{-1}), Fresnel transmission (70.2%), and crystal length. Results of this calculation are shown in Figure 13, where the round-trip transmission is plotted as a function of beam diameter of both the cavity mode waist and the external input beam (i.e., the off-axis pump), which are assumed to possess similar beam parameters. Each curve corresponds to a different GaAs crystal length. For this calculation, it is assumed that the



F'GURE 13. Round-trip transmission (oscillation condition) in a bidirectional linear resonator.

confocal parameter is greater than the crystal length. From the figure, we conclude that for reasonable crystal lengths and beam diameters, two-wave oscillation, and hence self-pumped conjugation, requires that the crystal be antireflection coated, which we are presently having done.

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APPENDIX A

FEEDBACK SCHEMES TO ENHANCE THE REFLECTIVITY OF BACKWARD STIMULATED PHOTOREFRACTIVE SCATTERING PHASE-CONJUGATORS

Ruth Ann Mullen, David M. Pepper, and George C. Valley, abstract and summary submitted to CLEO'89, Conference on Lasers and Electro-optics, Baltimore, MD (supported in full by ONR).

Submitted to CLEO '89

"Feedback schemes to enhance the reflectivity of backward stimulated photorefractive scattering phase-conjugators"

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We demonstrate that the reflectivity of a backward stimulated photorefractive scattering phase-conjugator can be increased and/or stabilized by the implementation of several feedback geometries which "seed" the stimulated scattering.

"Feedback schemes to enhance the reflectivity of backward stimulated photorefractive scattering phase-conjugators"

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Since the original prediction and discovery of phase-conjugation via backward stimulated photorefractive scattering (BSPS)[1], this effect has not been reported in additional crystals of $BaTiO_3$. Here we report the observation of a larger though sometimes unsteady BSPS phase-conjugate reflectivity of up to about 20% in another $BaTiO_3$ crystal sample and show that the BSPS reflectivity can be stabilized and/or appreciably enhanced by the purposeful injection of either phase-conjugate or partially noisy seeds. By analogy with stimulated Brillouin scattering, we explain that these reflectivity enhancements result from small amounts of feedback which can dramatically lower the threshold for stimulated scattering processes[2]. Finally, we compare our feedback geometries with several other geometries for photorefractive self-pumped phase-conjugation[3,4].

In the absence of feedback enhancement, the gain-length product in Reference 1 was in the range of 5 to 10, somewhat lower than is typically required in stimulated Brillouin scattering (where gIL = 20 to 30 at threshold). A top-view photograph (Figure 1) and associated line drawing (Figure 2) of the beam trajectory in the crystal (c=9.7 mm; a,b=7.0,6.1 mm, Sanders and Associates, 69K) during BSPS without feedback enhancement indicate that the laser beam fanned sharply to an angle of 13.2 degrees with respect to the c-axis, broke into a few bright filaments, and

then propagated along a fairly straight line for about 5.6 mm. The backward gain for this angle can be calculated[1], given a trap density N_T determined by a combination of separate steady-state and transient gain measurements in this crystal sample. Painting either the crystal's exit face or the exit surface of the index-matching cuvette with diffusely-reflecting white paint to increase the background scattering did not appreciably enhance the reflectivity.

Three distinctly different geometries not requiring index-matching fluid (Figure 3) were used to inject a seed into the BSPS interaction region. In figures 3a and 3b, the fanned light transmitted through th crystal is collected by a combination of two lenses, then focus d onto a reflector. In 3a, the reflector is a phase-conjugate or so that the seed is an exact phase-conjugate of the pump. This geometry is directly analogous to SBS oscillator/amplifier systems of Basov et al.[5] and others. In Figure 3b, the reflector is an ordinary mirror, resulting in a seed which is neither a conjugate nor a noise beam. The reflectivities of these two geometries were comparable, a steady 19.3% and an oscillatory (16 ± 5)%, respectively. When the seeds were blocked, the phase-conjugate reflections decayed away with time constants of 45 and 60 ms, respectively. The good fidelity of these systems is evident by noting that, in addition to being an amplifier and phase-conjugator, the first $BaTiO_3$ crystal also acts as a severe, non-linear aberrator because of the strong beam-fanning. Both of the above-described feedback schemes exhibited very good phase-conjugate fidelity in the presence of this very strong aberrator, with the phase-conjugate beam having roughly the same near-field beam diameter as the pump.

Another feedback scheme was originally demonstrated for SBS[2], and provides a seed that is both an exact phase-conjugate and which should also have exactly the right frequency shift (just as in Figure 3a). This geometry, shown in Figure 3c, exhibited high reflectivities even in a considerably shorter crystal (Sanders

69F; c=6.2, a=6.8, b=5.5 mm), oscillating sinusoidally between 22% and 44% at 1.4 Hz for 99 mW incident laser power.

While crystals with large enough gain-length products to sustain BSPS in the absence of feedback are not readily available, the three feedback schemes described above enable even very short or low gain crystals to exhibit BSPS.

Reflectivity, fidelity, and stability data on these and several other types of seeded BSPS geometries will also be discussed. Finally, the advantages of BSPS conjugators over earlier self-pumped geometries[3,4] for power scaling applications will be outlined.

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FIGURES:

1. Top-view photograph beam trajectory in $BaTiO_3$ crystal during occurrence of SPS. Experimental parameters: λ=514.5 nm, P 50 mW incident on the cuvette, cuvette located about 6 cm beyond the focal point of a 16 cm focal length lens, p-polarization.

2. Line drawing showing main features of Figure 1.

3. Three optical feedback configurations for providing a seed to lower the threshold for stimulated photorefractive scattering. (a) A phase-conjugate seed is generated by a separate crystal operating in the total internal reflection mode. (b) A relatively noisy seed is provided by the reflection of the fanned light from an ordinary mirror. (c) Phase-conjugate seeds for SPS are generated via four-wave mixing. The phase-conjugate seeds exactly re-trace the paths of the forward-going, fanning light, dramatically lowering the threshold for SPS.

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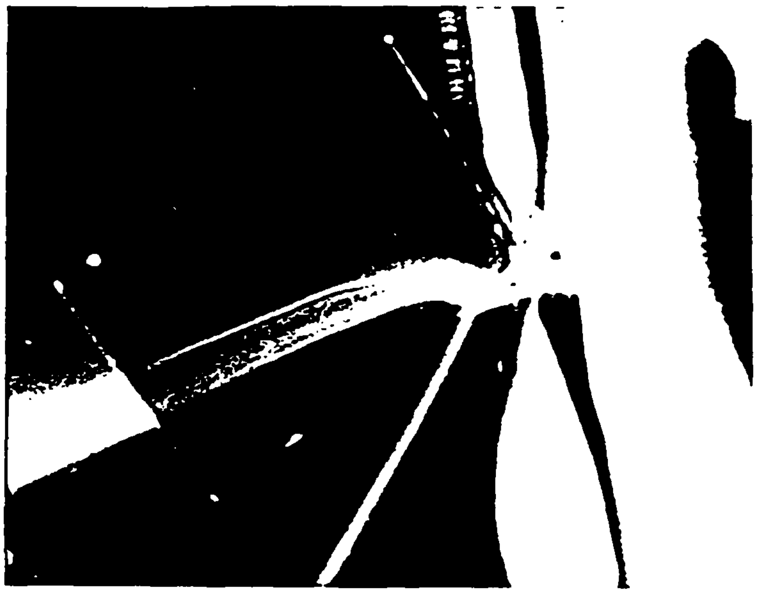

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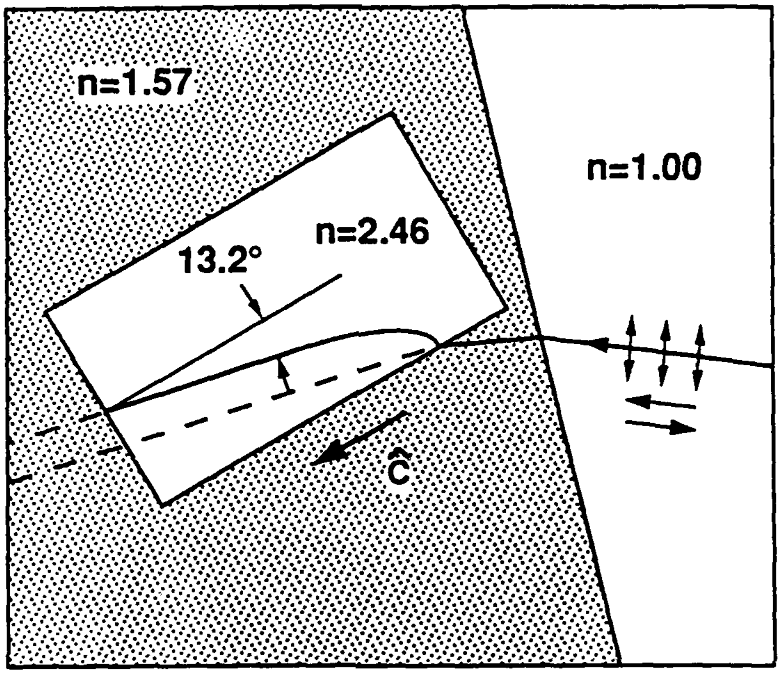

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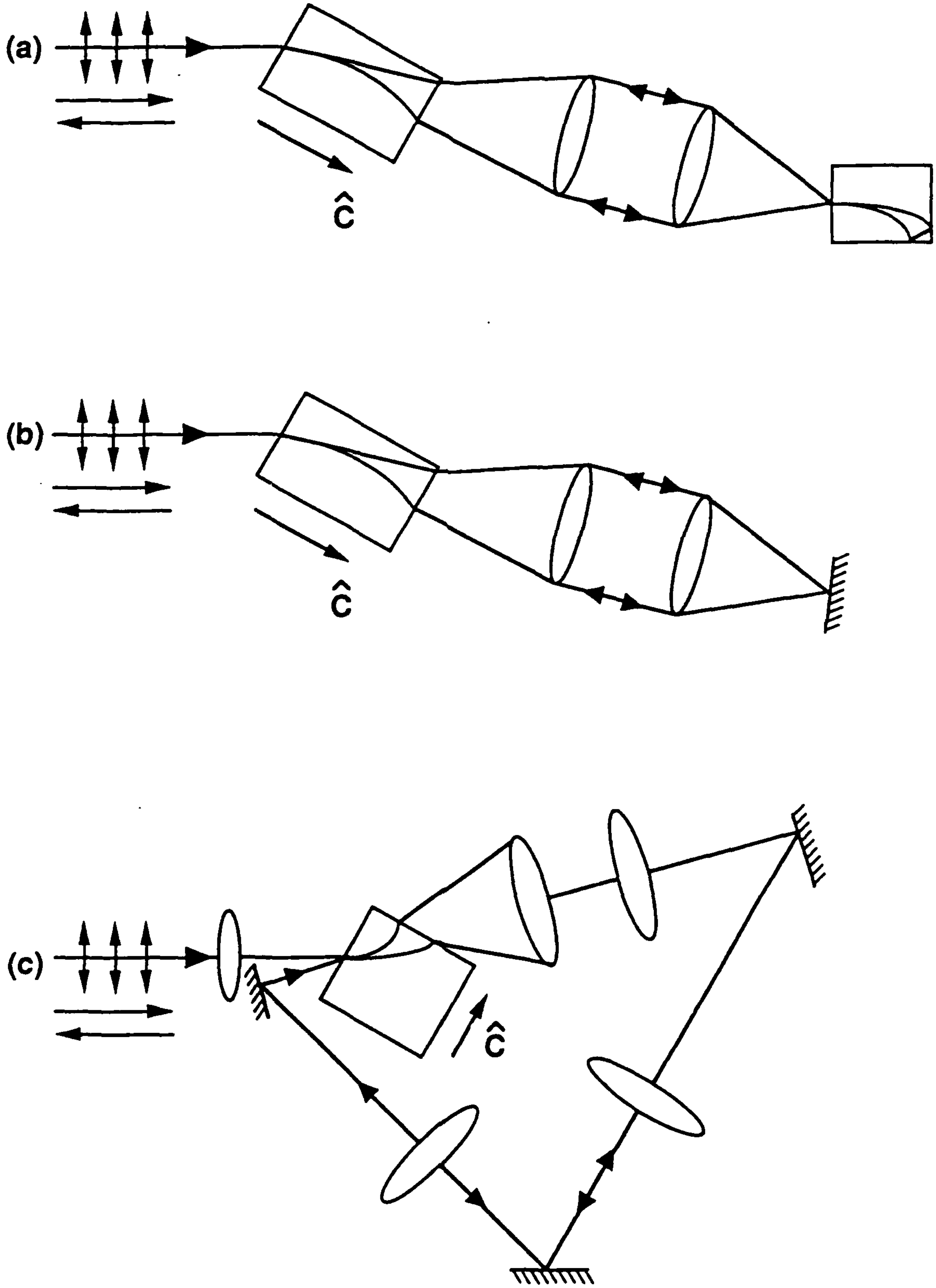

APPENDIX B

CONTROL AND CHARACTERIZATION OF SELF-PUMPED PHASE CONJUGATE REFLECTIVITY USING INCOHERENT ERASURE

G.J. Dunning, D.M. Pepper, M.B. Klein, and R.A. Mullen, abstract and summary submitted to CLEO'89, Conference on Lasers and Electro-optics, Baltimore, MD (supported in part by ONR).

CONTROL AND CHARACTERIZATION OF SELF-PUMPED PHASE CONJUGATE REFLECTIVITY USING INCOHERENT ERASURE

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We use an incoherent erase beam to increase the phase conjugate reflectivity of a self-pumped phase conjugate mirror by a factor of two. Selective erasure was also used to investigate gain-length product requirements in photorefractive crystals of $BaTiO_3$.

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There is a substantial interest in self-pumped, photorefractive phase conjugate mirrors due to the novel physics of operation and their potential use for devices. We use an incoherent erase beam to modify the grating formation in a self-pumped phase conjugate mirror (PCM), a technique which has been used both for device applications[1-3] and diagnostics[4]. In this presentation we have used selective erasure to produce significant increases in the phase conjugate reflectivity. We propose that this is due to the elimination of detrimental parasitic gratings formed during PCM operation. In addition, we find this erasure technique helpful for diagnosing the basic mechanism responsible for the self-pumped PCM.

In our experiments we have examined the phase conjugate signal from a self-pumped PCM as a function of local grating erasure. Feinberg[5] has shown that a SP-PCM has a threshold condition set by the coupling constant and effective length. This condition corresponds to an intensity threshold, if the coupling coefficient varies as $\gamma_o/(1+I_o/I)$. A threshold function may be produced, in theory, by illuminating the crystal to change the background conductivity. By doing this, only those portions of the input beam intense enough to write gratings will produce a phase conjugate. Illuminating the crystal with an erase beam which is incoherent with respect to the conjugate beam, locally reduces the modulation depth of the charge carrier and trapped charge gratings, thereby reducing the gain. In this way, varying the intensity of the erase beam should provide a means of adjusting the threshold of the self-pumped PCM.

In our experiments we were able to eliminate detrimental parasitic gratings in the crystal, with a consequential enhancement in the phase-conjugate reflectivity. The largest increase in phase conjugate reflectivity was obtained by illuminating the crystal from below with the erase beam focused in the region near the entrance face.

The results of one experiment are shown in Figure 1, where the phase conjugate return and erase beam are plotted as a function of time. The phase conjugate intensity is the solid curve and the erase beam is the dashed curve (there is a slight displacement of the recording pens). Initially only the 5145Å signal beam was incident on the crystal and the phase conjugate reflectivity had an average value of 30%. After 75 seconds into the experiment the erase beam was turned on, resulting in an initial reduction of the phase conjugate return to zero. After an additional 160 seconds, in the presence of the erase beam, the PCM output built up to a value which was 2 times the value obtained in the absence of the erase beam.

The experiment was designed so that we could simultaneously monitor the input beam and the erase beam. A schematic of the experimental layout is shown from the top in Figure 2. The self-pumped PCM operated at 5145Å and the erase beam was at 4880Å. The erase beam was spatially filtered and expanded to a diameter larger than the crystal for large volume erasure. For selective volume erasure a focusing lens could be placed in the beam one focal length from the crystal. The erase beam could be positioned in the crystal by using a translating mirror in conjunction with a rotating glass plate. A knife edge could be used to control which portion of the crystal was illuminated. A prism was used to direct the erase beam into the $BaTiO_3$ crystal from below[4]. The interaction region of the crystal was imaged onto a video camera. The phase conjugate signal generated was reflected by a beam splitter and imaged onto a detector or a second video camera.

In this talk we will also discuss experimental results measuring the turn-on times and enhancement factors as a function of illumination. In addition we present methods using selective erasure to investigate the gain-length product of self-pumped photorefractive phase conjugate mirrors.

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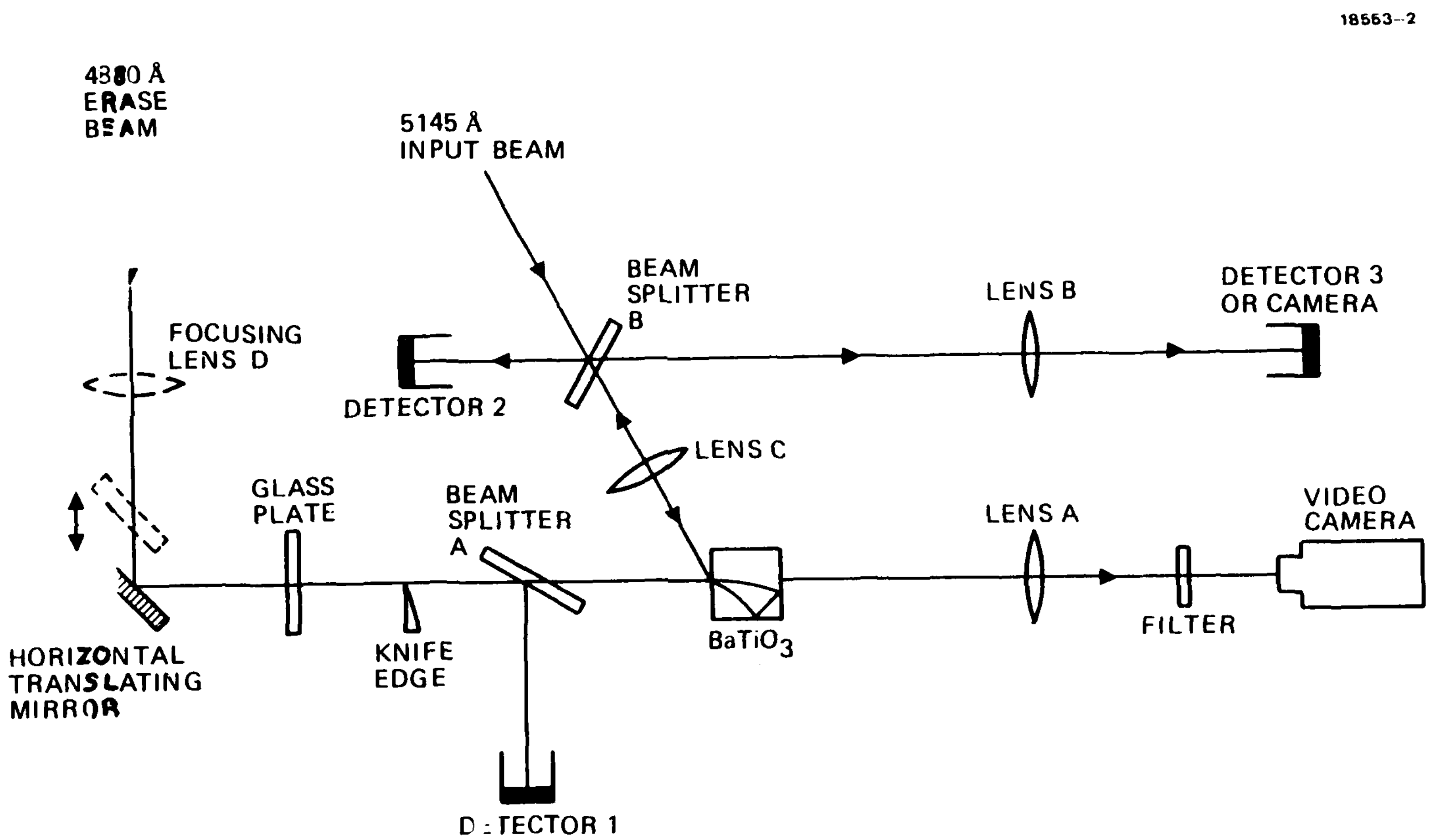
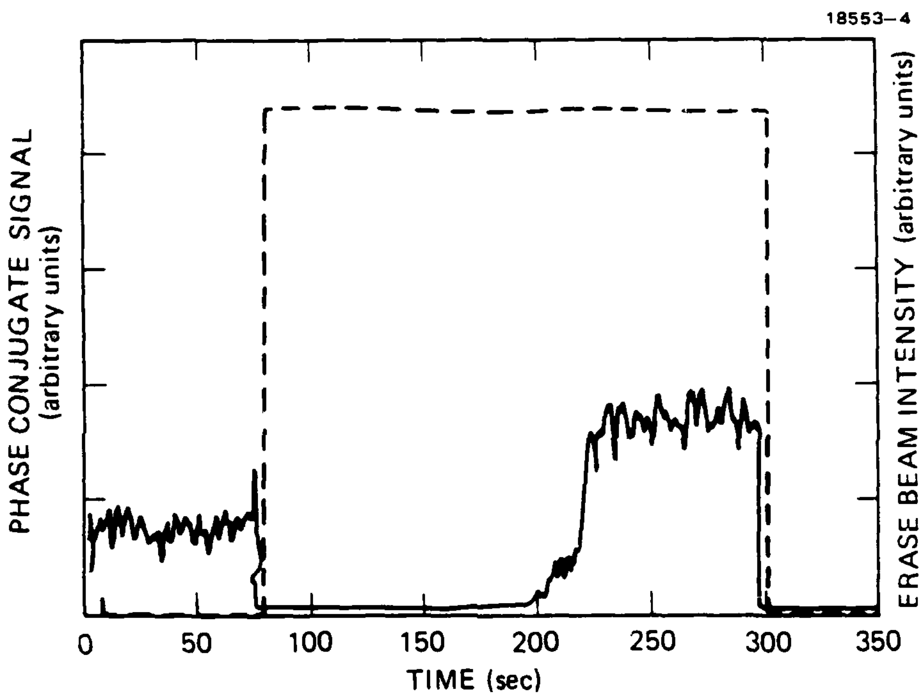
FIGURE CAPTIONS

Figure 1. Enhancement of phase conjugate signal from a self-pumped conjugator in the presence of erase beam. Phase conjugate return - solid curve. Erase beam - dashed curve.

Figure 2. Experimental layout (top view) allowing selective erasure, with control and monitoring of pump and erase beams.


18563-2
4380 Å
ERASE
BEAM
5145 Å
INPUT BEAM
BEAM
SPLITTER
B
LENS B
DETECTOR 3
OR CAMERA
FOCUSING
LENS D
DETECTOR 2
LENS C
GLASS
PLATE
BEAM
SPLITTER
A
LENS A
VIDEO
CAMERA
BaTiO3
FILTER
HORIZONTAL
TRANSLATING
MIRROR
KNIFE
EDGE
DETECTOR 1

TOP VIEW


18553-4
PHASE CONJUGATE SIGNAL
(arbitrary units)
ERASE BEAM INTENSITY (arbitrary units)
0
50
100
150
200
250
300
350
TIME (sec)

APPENDIX C

OBSERVATION OF DIMINISHED SPECULAR REFLECTIVITY FROM PHASE-CONJUGATE MIRRORS

Submitted to Physical Review Letters

(Submitted to Physical Review Letters)

Observation of Diminished Specular Reflectivity From Phase-Conjugate Mirrors

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Abstract

We observe that the *specular* reflectivity from the input face of a phase-conjugate mirror consisting of a single crystal of $BaTiO_3$ *decreases by over 600%* (relative to the standard Fresnel reflectivity value) upon the onset of phase conjugation, or wavefront reversal. Reasonable agreement with experiment is obtained using a model involving the destructive interference of the Fresnel-reflected beam with a series of phase-conjugate waves generated internal to the crystal. The basic diminishing effect should be universal and hence observable in most classes of phase-conjugate mirrors.

PACS Numbers:

42.65.Hw; 42.65.Ma; 78.20.-e

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The field of nonlinear optical phase phase conjugation[1] has attracted much interest in both applied and fundamental areas of quantum electronics since its inception in the early 1970's. Wavefront reversal has been demonstrated using myriad nonlinear optical mechanisms including stimulated scattering interactions (such as Rayleigh, photorefractive, Brillouin, and Raman) and parametric interactions (such as three-wave and four-wave mixing) in most states of matter. Both "self-pumped" and "externally pumped" classes of conjugator have been realized: in the former [latter] case, an external optical beam is not [is] required to initiate the process. Although the wavefront reversal nature of these interactions has been intensely studied, no study (to our knowledge) has been undertaken to characterize the *specular* reflection properties of phase-conjugate mirrors.[2]

In this Letter, we report on the observation of a significant diminishing of the specular

reflectivity from the input surface of a phase-conjugate mirror (PCM). In the case of a $BaTiO_3$ PCM, the near-normal specular reflectivity (in air) was observed to decrease from the standard Fresnel value of ≈17.8% to ≈2.8% upon the onset of the conjugation process. This striking decrease cannot arise simply from an intensity dependent refractive index change at the dielectric interface; this would require that the index decrease from ≈2.45 ($BaTiO_3$) to ≈1.4. The required nonlinear index would thus have to be orders of magnitude larger than any previously reported, given our operating intensities (≈W/cm^2).

In the experiments described below, we deduce that this diminishing effect stems from the destructive interference of a beam undergoing Fresnel reflection at the surface with a previously unreported beam emerging from the PCM. The latter beam stems from a sequence of successive conjugation interactions internal to the crystal: a "conventional" volume conjugator which leads to a wavefront-reversed replica, followed by a previously unreported conjugation process that occurs within one beam diameter of the front surface of the PCM and is mediated via a four-wave mixing[1] interaction. These two internal conjugate mirrors can be shown[3] to be locked in phase relative to each other for all incident angles and wavefronts. Moreover, the beams generated by this pair of conjugate mirrors combine to interfere destructively with the Fresnel-reflected beam --- thereby diminishing its intensity --- and, in the process, interfere constructively with the conjugate wave --- thereby increasing the externally measured phase-conjugate reflectivity of the crystal as a whole. The magnitude of the effect depends on the specific nonlinear mechanism(s) internal to the medium, and thus may be material, intensity and geometry (angle, beam size) dependent. In any case, the basic diminishing effect should be universal, and hence observable in other classes of self-pumped and externally pumped PCMs.

In what follows, we first discuss the basic effect, followed by a description of experimental observations that validate the above conjecture, while ruling out other potential mechanisms. Various experimental diagnostics lend credence to our model, including the spatial,

temporal, polarization, angular, and frequency dependence of the interacting beams,[3] as well as selective optical erasure of the various induced gratings within the crystal. We conclude with a comparison of experimental measurements with model calculations.

We assume that all the interacting fields are monochromatic at radian frequency ω_q, and p-polarized, with the $q\underline{th}$ field denoted by

$$\mathbf{E}_q(\mathbf{x}) = \mathbf{A}_q(\mathbf{x})e^{i[\omega_q t - \mathbf{k}_q \cdot \mathbf{x} + \varphi_q(\mathbf{x})]} , \tag{1}$$

where $\mathbf{A}_q(\mathbf{x})$ is real, $\mathbf{k}_q$ is the field wavevector, $\mathbf{x}$ is the propagation direction, and $\varphi_q(\mathbf{x})$ is a phase factor depicting the wavefront of the field. The basic geometry, along with the two conjugate regions are sketched in Figure 1. The volume phase-conjugate region, denoted by PCM_1 and possessing an amplitude reflectivity r_1 is, in our case, due to self-pumping[4] in $BaTiO_3$. (The detailed mechanisms describing PCM_1 are of no consequence to realize the diminishing effect; all that is required is the presence of a conjugate wave within the medium.) Given an external input beam, $\mathbf{E}_1$, at frequency ω, the field entering the crystal is $\mathbf{E}_2 = t_F\mathbf{E}_1$, where t_F is the amplitude Fresnel transmission coefficient of the air/crystal interface. The result of PCM_1 is to generate a conjugate replica of $\mathbf{E}_2$, defined to be $\mathbf{E}_3$, which is Stokes shifted in general, at frequency $\omega-\delta$:

$$\mathbf{E}_3(\mathbf{x}) = t_F^* r_1 \mathbf{A}_1(\mathbf{x})e^{i[(\omega-\delta)t + \mathbf{k}_1 \cdot \mathbf{x} - \varphi_1(\mathbf{x})]} , \tag{2}$$

The near-surface conjugation region, denoted by PCM_2 and with amplitude reflectivity r_2 (in magnitude), is mediated by a nearly degenerate four-wave mixing process[1]: the two "pump" beams required for the interaction consist of the incident beam within the crystal ($\mathbf{E}_2$) and its conjugate replica, $\mathbf{E}_3$. These two fields yield a conjugate pair of pump beams, resulting in a phase-locking of both PCM's. The "probe" beam incident upon PCM_2, denoted by $\mathbf{E}_4$, is derived

from the fraction of the conjugate wave generated by PCM_1 which is internally reflected at the entrance interface into the interaction region of PCM_2, so that $E_4 = r_F E_3$, where r_F is the amplitude Fresnel reflection coefficient of the crystal/air interface. As a result of the interaction of the probe wave with PCM_2, a conjugate wave, E_5, at frequency $\omega = [\omega+(\omega-\delta)-(\omega-\delta)]$ is generated:

$$\mathbf{E}_5(\mathbf{x}) = |t_F r_1 A_1|^2 \, t_F r_F^* r_2 \, A_1(\mathbf{x}) e^{i[\omega t - \mathbf{k}_1 \bullet \mathbf{x} + \varphi_1(\mathbf{x})]} \quad . \tag{3}$$

A fraction of this wave, $\mathbf{E}_6 = t_F \mathbf{E}_5$, exits the crystal in the direction of the specularly reflected incident beam, $r'_F \mathbf{E}_1$, where r'_F is the amplitude Fresnel reflection coefficient of the air/crystal interface. These beams, as well as subsequent reflections, coherently combine, resulting in a total field

$$\mathbf{E}_{specular}(\mathbf{x}) = \{ r'_F + \; |t_F r_1 A_1|^2 r_2 [t_F^2 r_F^*] \; + \; ... \} \; \mathbf{E}_1(\mathbf{x}) \quad . \tag{4}$$

Since the phase factor of the product $t_F^2 r_F^*$ differs by π relative to that of r'_F, the internally generated wave *destructively* interferes with the specularly reflected incident wave, yielding the diminishing effect. Note that the exiting wave has the same radian frequency (ω) and phasefront $[\varphi_1(\mathbf{x})]$ as the initial specularly reflected wave, $r'_F \mathbf{E}_1$.

The experimental apparatus consists of a single domain crystal of $BaTiO_3$, with a single longitudinal mode cw argon ion laser (λ=514.5nm; I≈440mW/cm^2) as the optical source. For this study, both 0°-cut and 45°-cut crystals[5] were employed. Detectors are used to monitor the specularly reflected beam, conjugate wave, and residual on-axis beam transmitted through the crystal (within a ≈1° field-of-view).

The specular reflectivity of the 45°-cut sample as a function of the angle of incidence, θ, for both linear polarization states is shown in Figure 2. For s-polarization, reasonable agreement is

obtained with the standard Fresnel reflection coefficient using the accepted values[6] for the refractive index of $BaTiO_3$. For this polarization and crystal orientation, self-pumped conjugation does not occur. Similar results were obtained for both crystal cuts.

For p-polarization, a dramatic decrease in specular reflectivity is seen relative to that calculated using the standard Fresnel relations. At near-normal incidence, the reflectivity is 600% smaller than the theoretical value for the 45°-cut crystal, and is 30% smaller than the calculated value for the 0°-cut sample. Since the diminishing effect is seen to occur for all angles of incidence, the effect is not due to a fortuitous succession of internal reflections and subsequent interference with the Fresnel-reflected beam. Thus, a well-defined internal beam (in angle and phase) emanates from the PCM in order to result in the diminishing effect.

When the crystal is angularly dithered about an axis normal to the plane of incidence at a rate (≈100Hz) faster than the characteristic grating build-up time, and through an excursion ($\Delta\theta \approx 0.5°$) in excess of the Bragg acceptance angle, the conjugate wave as well as beam fanning[1] both vanish. Under these conditions, the angular dependence of the specular reflectivity for the p-polarization state is seen to agree reasonably well with the Fresnel-calculated values, as plotted in Figure 2. Thus, the diminishing effect has its origins in the nonlinearly induced gratings, and is not due to an anomalously large nonlinear index or other scattering effect.

The temporal evolution of the specularly reflected beam, conjugate wave, and on-axis crystal throughput is shown in Figure 3. Since the onset of beam fanning (which temporally precedes the conjugation process) deflects most of the beam off-axis, the output of the on-axis detector is seen to decrease in time. On the other hand, the conjugate wave build-up is temporally correlated with the decrease in the specularly reflected beam. Thus, the diminishing effect is intimately related to the presence of the conjugate wave within the medium, and is not related (directly) to beam fanning.

Finally, an incoherent beam with an intensity ten times that of the probe beam was

employed to selectively erase[7] small ($\approx$ 0.2mm diameter) spatial regions of the optically induced gratings in the crystal; illumination was normal to the plane of incidence. In one case, the central portion of the crystal was illuminated by the erase beam, resulting simultaneously in both a restoration of the specularly reflected beam to its Fresnel-calculated value and a complete vanishing of the conjugate beam. When the erase beam illuminated the crystal near the input surface, the specularly reflected beam was restored to its Fresnel-calculated value. In addition, a concomitant 40% decrease was observed in the conjugate reflectivity, attributed to optical scattering of the erase beam within the crystal. Hence, we conclude that two distinct grating regions exist within the crystal: one which is required for the volume conjugator, and a second near-surface conjugator that contributes to the cancellation of the specular component.

To analyze our system, we generalized the existing diminished specular reflectivity model[8] to include *two* distinct, yet phase-locked PCMs, obtained by summing the terms in equation (4). Our model predicts a diminished (power) specular reflectivity ($R_{specular}$), given the Fresnel reflectivity (R_F), and that of the two internal PCMs ($R_{1,2}$):

$$R_{specular} = R_F\{[1-(R_1R_2)^{.5}]/[1-R_F(R_1R_2)^{.5}]\}^2 \ , \qquad (5)$$

where $R_i = |r_i|^2$. The model also predicts an enhanced conjugate reflectivity, $R_{conjugate}$:

$$R_{conjugate} = R_1(1-R_F)^2/[1-R_F(R_1R_2)^{.5}]^2 \ . \qquad (6)$$

Given the externally measured quantities, $R_{specular}$ and $R_{conjugate}$, equations (5) and (6) can be solved for the reflectivities of the internal PCMs. We now use the value for the reflectivity of the volume conjugator, R_1, and typical values for the parameters of the near-surface conjugator, PCM_2, to calculate[3] its reflectivity, R'_2. In our case of a photorefractive nonlinearity, R'_2 is

calculated using a depleted pump analysis[9] involving the two-wave gain-length product,[10] and the amplitude ratios of the three interacting beams ($\mathbf{E}_2$, $\mathbf{E}_3$, and $\mathbf{E}_4$). Using the values of R'_2 and R_1 in equation (5), we arrive at a predicted value of the diminished reflectivity ($R'_{specular}$), which we compare with our measurements. Calculations for an internal angle of i-cidence of 10° are tabulated in Table 1. The difference in the magnitude of the diminishing effect for the two crystal cuts arises primarily from the two-wave gain-length products: 0.376 and 1.88, for the 0° and 45° cut crystals, respectively. The close quantitative agreement of theory and experiment for the diminished specular reflectivity is fortuitous, given the variation of $BaTiO_3$ material parameters and the precise beam overlap geometry. Nonetheless, the observed diminishing effect for the two crystal cuts, coupled with the series of consistent experimental parameter studies, give us confidence that the physical mechanism is well characterized.

In conclusion, we have observed a significant diminishing of the specular reflectivity in self-pumped phase conjugate mirrors. We have since observed similar diminishing effects using a self-pumped conjugator in the "external loop" configuration[11] in $BaTiO_3$ and in $KNbO_3$ (Ref. 12), as well as in $BaTiO_3$ using the standard externally pumped four-wave mixing geometry.[13] The basic diminishing effect should be universal and hence observable in other classes of PCMs, including resonantly enhanced nonlinear media such as sodium vapor;[14] and in stimulated Brillouin scattering mirrors,[1,15] in which case the near-surface conjugate region may be mediated via a Brillouin-enhanced four-wave mixing process.[16] A practical consequence of the diminishing effect is that unless taken into account, one can inadvertently over-estimate the internal volume phase-conjugate reflectively, as well as under-estimate the (linear) refractive index. The diminishing effect is expected to be most pronounced in materials possessing large linear refractive indices and nonlinear susceptibilities, such as semiconductors and electro-optic oxides.

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Table Caption

1. Calculated and measured specular and conjugate reflectivities for both 0° and 45° cut crystals using p-polarized light at an internal [external] angle of 10° [≈24.2°].

TABLE 1

Crystal Cut	SPECULAR REFLECTION			CONJUGATE REFLECTION		
	Calculated Fresnel Refl. [R_F]	Observed Specular Refl. [$R_{specular}$]	Calculated Specular Refl. [$R'_{specular}$]	Meas. R(PCM) [$R_{conjugate}$]	Calc. $R(PCM_1)$ [R_1]	Calc. $R(PCM_2)$ [R'_2]
0°	12.7%	8.7%	9.9%	42.6%	53.7%	3.2%
45°	13.2%	2.4%	2.1%	61.4%	68.4%	59.3%

Figure Captions

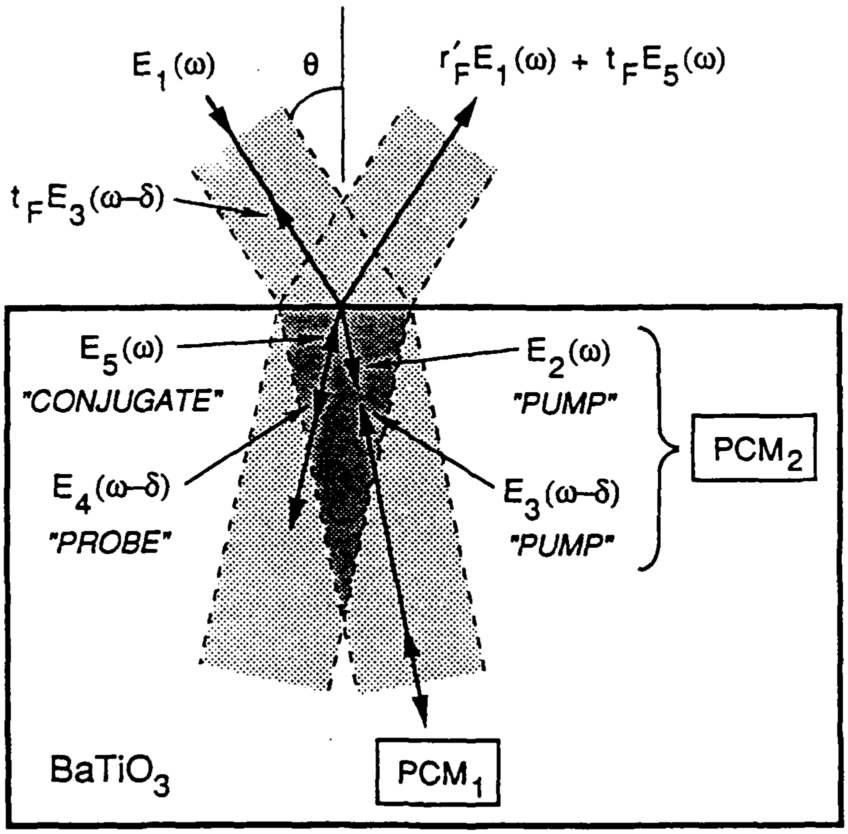
1. Two phased-up conjugation regions that result in a diminished specular reflectivity. PCM_1: volume conjugator; PCM_2: near-surface conjugator (shaded area). Beams are displaced for visual purposes.

2. Specular reflection data for the 45°-cut crystal. S-polarization (dots): no conjugation and beam fanning occur for this polarization. P-polarization: stationary crystal (squares) and angularly dithered crystal (triangles); self-pumped conjugation and fanning occur [do not occur] for the stationary [angularly dithered] crystal. Solid curves: Calculated Fresnel reflectivity for an air/$BaTiO_3$ interface using $n_o = 2.488$ and $n_e = 2.423$, after Ref. 6. (Note: Best fit to our data [dashed curves] was obtained using $n_o = 2.354$ and $n_e = 2.310$; the origin of the small discrepancy is not clear, yet does not affect the basic premise of this paper).

3. Oscilloscope trace of the temporal evolution of the conjugate wave (D_1), specular reflectivity (D_2), and transmitted beam through the crystal (D_3). For this measurement, a 0°-cut crystal was employed. The conjugate wave build-up to 42.6% reflectivity (at ≈15 seconds after turn-on) is temporally correlated with the diminishing of the specular reflectivity (from 12.7% to 8.7%); beam fanning (resulting in a rapid decrease in transmission) occurs much earlier in time (at ≈2 seconds after turn-on).

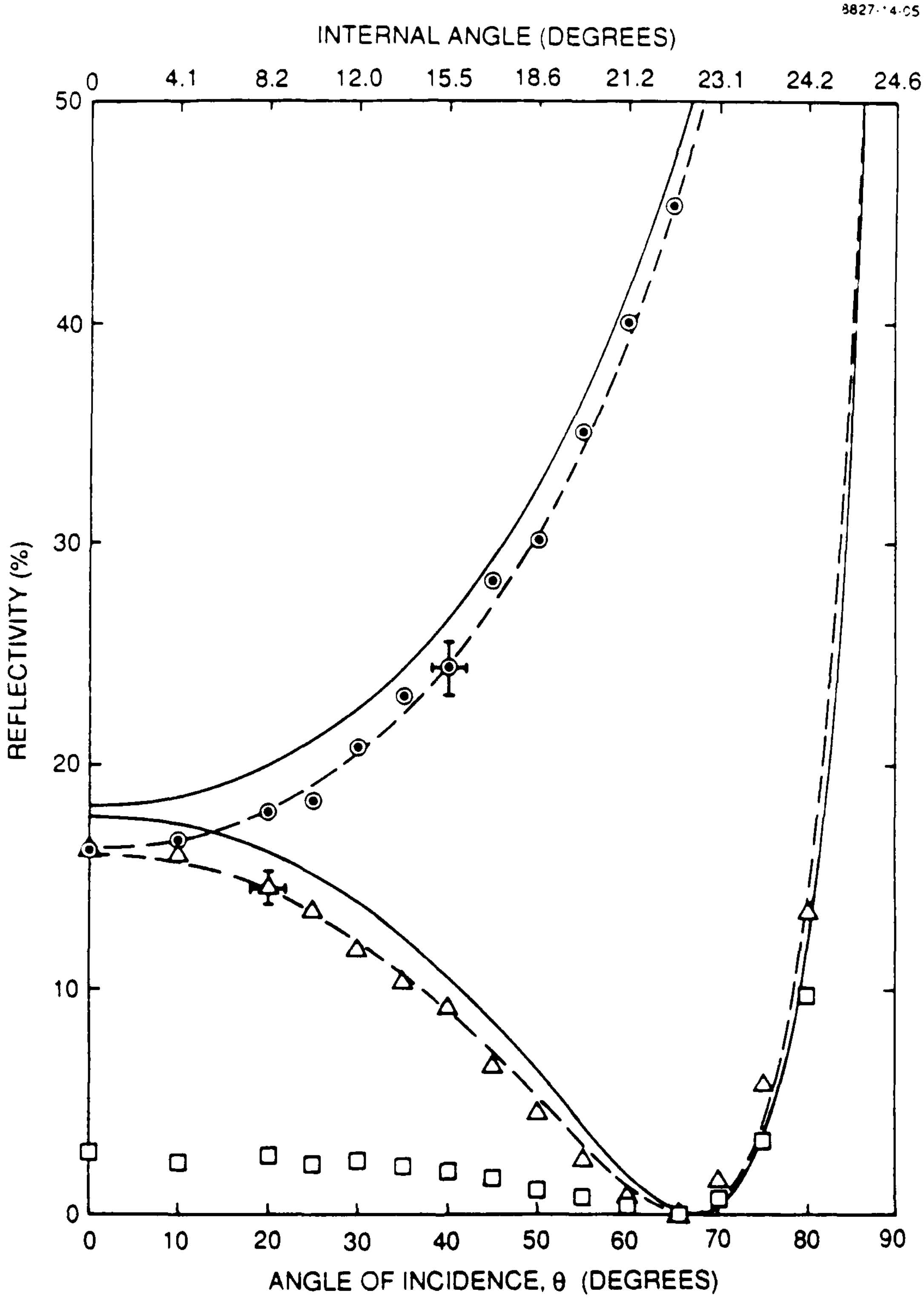
TOP ↑

C8827-14-04R1

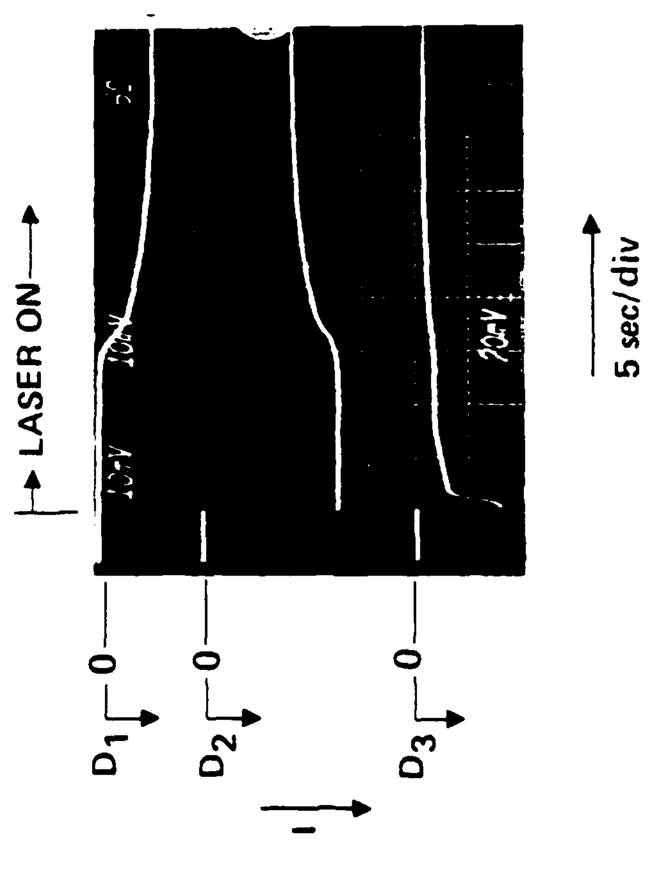


PEPPER
FIG. #1

PEPPER
FIG. [redacted] #2
TOP ↑



PEPPER
FIG. # 3 TOP



APPENDIX D

FEEDBACK-ENHANCED BACKWARD STIMULATED PHOTOREFRACTIVE SCATTERING (FE-BSPS)

Invited poster paper, 19th Winter Colloquium on Quantum Electronics, Jan 8-12, 1989

Feedback-enhanced
backward stimulated photorefractive scattering (FE-BSPS)

Ruth Ann Mullen and David M. Pepper

We demonstrate that the reflectivity of a backward stimulated photorefractive scattering phase-conjugator can be increased and/or stabilized by the implementation of various feedback geometries which "seed" the stimulated scattering.

Invited poster paper to be presented at the 19th Winter Colloquium on Quantum Electronics, Jan 8-12, 1989.